the human touch

A fundamental factor in mechanical design

By James G. Skakoon and Michael Wiklund

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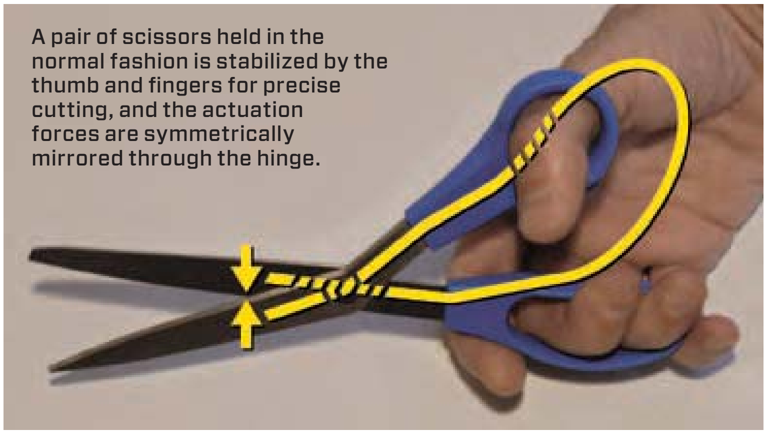
Power grips include the perpendicular, for using the hammer, and torque, for using the screwdriver.

Human factors engineering in today's best consumer products is obvious. Compare, for example, the ease of the touch-screen interface on a tablet computer with the personal computers from the past. Using gestures like swiping across the screen to move an object is more natural than clicking and dragging with a mouse. But not all devices are sleek electronic gadgets. Our lives are filled with ordinary mechanical tools and machines, which computers simply can't replace.

Human factors engineering of mechanical tools and devices is taken for granted. After all, don't we all have experience with mechanical gadgets, even if only a can opener or kitchen spatula? Mechanical devices are far less complicated than a software user interface with multiple operating modes. Mechanical devices usually perform a single task, or closely related ones, and provide immediate tactile and visual feedback. Serious errors in the human factors of mechanical devices become obvious enough with prototypes, usability testing, and actual use, right?

Joel Marks of WorkTools Inc. thinks

differently. Marks is a prolific inventor of shop and office tools, including the PowerShot forward-acting staple gun. "An important method for small hand-held devices is a holistic effort where the industrial design and mechanical means are developed at the same time, and, if possible, by the same person or team. This is most directly to the point of human factors," he said, adding, "Our newer products have all been done this way."



A pair of scissors held in the normal fashion is stabilized by the thumb and fingers for precise cutting, and the actuation forces are symmetrically mirrored through the hinge.

Designers need to be familiar with basic ergonomic standards and guidelines for their industries. In the mechanical area, for example, these include anthropometric data describing the range of human size, shape, strength, and reach. How to design devices so they do not promote hand fatigue and repetitive stress injuries is another area for designers to be familiar with. According to Marks, however, "There are few, if any, formal disciplines that teach about devices that are hand-powered and -held."

But understanding and explicitly managing user-applied forces, reaction forces, and the resulting motion constitute a large part of human factors engineering (HFE) in mechanical design. These are essentially mechanical engineering tasks, and mechanical design engineers do not need specialized training to apply some of the basics.

▶▶▶ FORCE FACTORS

Let's start with three fundamental forces in tools and other mechanical devices: stabilization, actuation, and opposition.

Consider, for example, how we hold and operate tin snips or scissors. Holding a pair of scissors in the normal fashion—with thumb and fingers—stabilizes the scissors. The finger and thumb holes allow a firm grip and a precise position. Shearing is initiated with a squeezing action, which is the actuation. The opposition forces are symmetrically mirrored through the scissors' hinge.

Although you could move one blade with one hand, the other with the other, like a large bolt cutter, this proves rather clumsy for precise cutting. This example reveals an important concept for human factors in mechanical design: the path of the forces, or "load path." Newton's third law of motion (i.e. for every action there is an equal and opposite reaction) says that the thumb's force transmitted to one blade is opposed by the fingers' force transmitted to the other blade, converging at the paper to shear it. All forces balance each other exactly, as Newton's law demands, and do so through a closed load path defined by blades, hinge, thumb, hand, fingers, and paper. Managing forces and motion in mechanical tools, devices, and controls means, above all, defining all the closed-loop load paths. Most designs will benefit from short, direct load paths for all the forces involved.

▶▶▶ GET A GRIP

Stabilization of mechanical devices is often (but not always) accomplished by gripping the device. Exceptions are devices that are immovable or attached to a heavy object, like control knobs and switches on machines, instruments, and vehicles.

Grips vary with each type of tool and also by individual preference, but a few common grips recur in most products. It is convenient to think of grips in four categories: power, pistol, squeeze (or scissors), and precision.

An important early step in mechanical HFE is to select the preferred grip or grips. Making invalid assumptions about how users will grip a product is a common error among designers, according to Jason Quick, a lecturer in the School of Art and Design at the University of Wisconsin-Stout. Quick, who has degrees in both mechanical engineering and industrial design, is a former human factors engineer at NASA's Marshall Space Flight Center.

"An expert designer on a product will grip something a certain way, and say this is how it's supposed to be used, without doing the field testing on early prototypes to validate those assumptions about what the user interaction is," Quick said. Therefore, it is imperative to consider—and confirm—all the variations of customary grips when designing a hand-held instrument or machine control.

Two variations of the power grip are a saw grip (action parallel to the forearm) and a hammer grip (action perpendicular to the forearm). Another is the power torque grip, which is used, for example, on large screwdrivers. The grip is the same—handle held tightly in the palm using the fingers and thumb—but the action is rotation about the forearm.

Particularly important variations are those that require a secondary actuation, as is characteristic of pistol grips. Actuation can come from the fingers or thumb, sometimes more than one, and even from those on the other hand.

Pistol grips, however, are not particularly well-suited to accurate positioning according to David Chastain, a program manager at Cambridge Consultants, a product design firm. "It's thought [by designers] that a pistol grip is a good fine-motor control grip, and, in fact, it's not," he said. Chastain explained that with a pistol grip, you move whatever you're holding with your wrist, which isn't nearly as good at accurate positioning as fingertips might be. "And you're trying to finely control a trigger, or finely actuate buttons at the same time as you're wanting your wrist to do the locating of the device," he added.

Precision grips use only the fingers rather than the full hand as power grips do. An external precision grip uses thumb and fingers with the instrument outside the hand, as when we write. Internal precision grips place the instrument inside the hand, or in the palm, but still use only the thumb and fingers for stabilization and actuation. A surgeon often uses an internal precision grip when wielding a scalpel, just as you might when using a steak knife. In many instances with this grip, people place the index finger atop the instrument for improved precision when applying force.

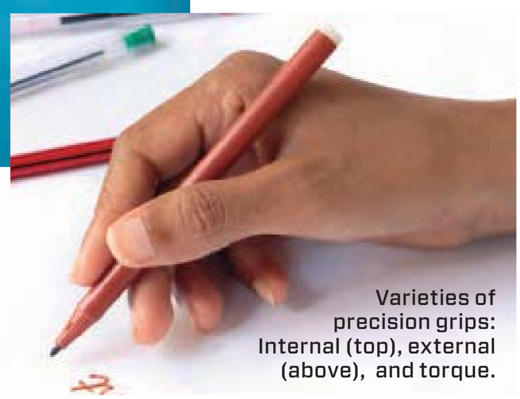
One version of a precision torque grip works with a jeweler's screwdriver. The spinning nut on the end opposite to the bit rests against the palm or forefinger for accurate aligning and for added driving force. But precision torque grips are ubiquitous, so we hardly notice how common they are. We adjust every rotating knob and turn every key with this grip. Because it is so easy to use, so familiar, and so precise, it is a preferred method for finely adjusting almost any input device.

▶▶▶ ACTUATE THE POSITIVE

Not only do users stabilize devices, they operate them; that is, they actuate them. A primary actuation occurs directly through the stabilization grip, as with a saw, hammer, pliers, or screwdriver. A secondary actuation occurs through a separate path that is independent of or indirectly linked to the grip. But this definition is more gray than black or white. The trigger actuation of a power drill's pistol grip is clearly an independent, secondary actuation. But using tweezers, for example, combines the gripping and actuating forces within the same path through the thumb and fingers.

A real concern with actuation is how the actuation force is opposed—remember Newton's Law. That is why, for example, "squeezing the trigger" is so important for accuracy in target shooting. Some hand-operated staple guns exhibit poignantly bad behavior in this regard. They are held with a squeeze grip, but because they often require a large arming force, stabilizing them accurately during firing can be challenging. Actuation is not independent of the stabilization because the forces for these interfere with each other.

Being the machines that they are, devices and tools transform the direction and magnitude of forces. Above all, they provide a mechanical advantage, which can be used to improve the feel or the control of a mechanism, tool, or actuator. The mechanical advantage of pliers or tin snips is obvious enough, but a subtler example is detent positioning of a rotating knob. Consider a typical automobile fan switch. Each setting, off, low, medium, and high, has its own stable position. This is a result of a slight, relative mechanical disadvantage when leaving one position, and a mechanical advantage when entering the next. The force required to rotate the knob changes enough for us to feel a position, and for the knob to remain in it.



Varieties of precision grips: Internal (top), external (above), and torque.

▶▶▶ MOVING ON

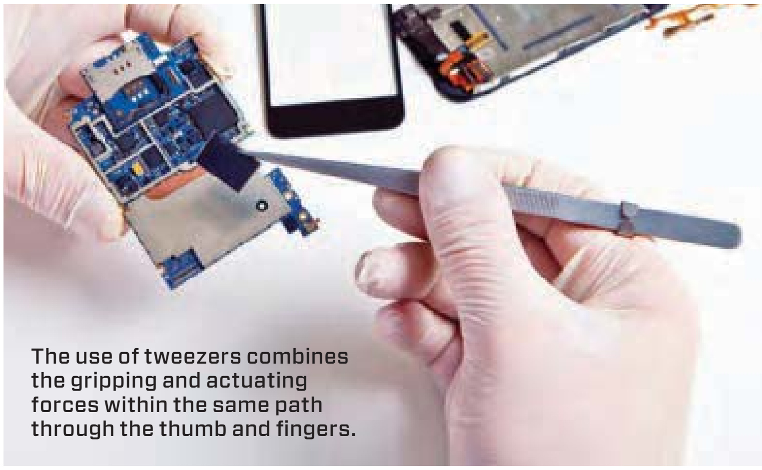
Force alone is rarely the goal; it is more often motion, or a mix of force and motion. With tools and mechanical devices of all kinds, we create, arrest, limit, and regulate movement. If we supply a force to a tool or mechanism, the resulting accelerations and velocities are governed first by any mechanical advantage the machine provides, then by the system's resistance to motion. This resistance comes from mass, springs, friction, or occasionally magnetism, and is defined by basic physics: $F = ma$ comes immediately to mind.

Instances of mechanical systems requiring HFE characterized predominantly by mass are rare. A hammer is one. But remember that weight is mass times gravity, and weight, too little or too much, can be a big concern in human factors. If your device or mechanism is massive, you'd better include a mechanical advantage or counter-balancing. Your device could also be too light so that it moves when controls or switches are actuated.

More often, it is the displacement or velocity that creates the dominant resistance to motion. Springs manifest a force when displaced, and store energy as well. All solids act like springs when deformed, so a component doesn't have to look like a traditional spring to act like one. Moreover, any force acting on any solid will deform it. But the "spring rate" for some systems can be so high that they act more like solid stops than springs. Describing a spring is simple: the more you compress it, the higher the force, and the more energy it stores.

Spring design in general, and spring rate and preload in particular, are important, yet often overlooked characteristics in HFE. Take, for example, a pushbutton on a computer keyboard. You know a good one when you feel it, but why it is good depends largely on the preload and spring rate.

Anthropomorphic data and standards might guide you on the correct force and the proper travel for a button. But they won't tell you that many good pushbuttons employ a preloaded spring and a relatively low spring rate. The force at the


The use of tweezers combines the gripping and actuating forces within the same path through the thumb and fingers.

start of motion is very close to the force at the end, or at least doesn't increase too rapidly. Moreover, the very best examples will incorporate an increasing mechanical advantage, which effectively reduces the spring rate with button travel. The result is an "avalanche" effect wherein a convenient force starts the motion, which continues with little or no additional force until the button hits bottom, unambiguously signaling a successful push. An extreme example is a "snap-acting" button, which is distinguished more by a precipitous drop in actuation force than by any rise to it. Contrast this with a button that requires a noticeably increasing force to fully push, or worse, that has a stepped increase in force near the end of its travel, as some latching buttons do. You are never quite sure if you've pushed it fully or not.

In its role of resisting motion, friction is more complicated. First, there are three types of friction to consider, static, sliding, and viscous, each with different effects in HFE.

Static friction prevents movement until a "breakaway" force is reached, after which sliding friction takes over. Static friction behaves, in part, much like a preloaded spring, but cannot store and return energy. Sliding friction occurs during movement between two contacting surfaces. It is commonly, if poorly, approximated to be independent of speed. Sliding friction behaves, in part, like a spring being compressed, but again cannot store and return energy, and does not increase with displacement. Static friction and sliding friction together constitute Coulomb friction.

Tightening a bolt or a nut with a wrench exemplifies Coulomb friction. The wrench handle affords a mechanical advantage to overcome the static torque. Once this is overcome, the wrench turns, at first with less torque than was required to start it, but then with increasing torque as the bolt tension climbs. The required torque is largely independent of rotational velocity, and the bolt or nut doesn't back off when wrenching is stopped.

But using friction to control motion can be perilous, according to David Chastain. "It's very hard to get uniform, constant friction that doesn't change over time." he said. But Chastain cited the hinges on laptop computer screens as one successful design example, calling them, "amazingly compact and simple little devices...that allow motion, but apply a uniform amount of friction."

Viscous friction also creates a force to resist motion, but the effect is proportional to speed. Moreover, there is no "starting force" as with Coulomb friction. This behavior—no starting force and speed-dependent resistance—makes viscous friction exceptionally valuable for precise positioning. Familiar examples are the volume control knob on high-end audio components and the focus knob on optical microscopes. They turn easily, while producing a sense of smooth resistance to motion, and can be moved to an exact position with little over- or undershoot.

Summarizing, controlling motion in HFE means managing these seven fundamentals of dynamics: mechanical advantage, mass, spring characteristics, static friction, sliding friction, viscous friction, and magnetic attraction.

Of course, these items can be rigorously analyzed, but this is seldom possible within time and cost constraints, but neither is it always necessary to improve the handling of mechanical devices and controls.

▶▶▶ GOOD AND EVIL AMONG US

A visit to a kitchen appliance showroom can instruct us about load paths and opposition forces. With some of the countertop blenders and coffee makers, attempting to push the operating buttons will move the appliance across the counter; you cannot push the buttons without stabilizing the appliance with your other hand. One clever—or inadvertent—solution allows one to push down with fingers on a horizontal surface of the housing, while simultaneously pushing a button with the thumb on the same hand. But the best solutions use a load path that manages stabilization, actuation, and opposition to advantage. Some small appliances orient the buttons to be pushed downward, so the counter-top opposes the button actuation. Others use rotary input switches; the footprint and weight create a stabilizing moment adequate to oppose the actuation.

Oven and dishwasher doors offer an instructional comparison of mechanical human factors. Performance and safety requirements aside, dishwasher doors are much more pleasing to operate, especially if they have a "squeeze to release" latch. Most are spring-balanced almost perfectly, and require little effort to open or close. They latch tightly, yet pop open with almost no effort. The unlatching action is independent of the opening action, with two separate load paths, providing excellent control to both.

Many oven doors stay in intermediate and end positions with stout detents. Some doors are not spring-balanced particularly well. Neither is there adequate frictional damping to arrest motion, nor viscous damping to slow it.

To open such doors, one must pull quite hard to overcome the closing detent, after which the door wants to fly open. It is irresistibly drawn to the mid-travel detent whether one wants it there or not. When closing, the door is again irresistibly drawn to both mid-travel and closing detents, slamming shut with a thud.

Of course, we rarely notice, being adapted to this behavior by custom. If you design oven doors, you'd be wise not to stray too far from this custom. However, if you intend to design the next fad in kitchen appliances, you'd do well to consider the load paths, actuation forces, and resistance to motion. Your door will no doubt operate more pleasantly than many oven doors.

In hand-held staple guns, there are two load paths: the first is the lever action path that fires the staple, the second the positioning and stabilization path. When a staple is fired, however, there is an opposition force that pushes the stapler away from the work piece, which must be opposed through the stabilization path. Many of these staplers are heavy duty models and require substantial squeezing force. You put so much effort into squeezing them that the stabilization force can suffer. You don't always get the staple where you want it, and you don't always drive it home.

Joel Marks's invention, the PowerShot forward-acting staple gun, addresses these issues. "The forces are over the exit area," Marks said when describing his invention. About the prior art, his patent states, "Efficient one handed operation... is not possible. To press down upon the front end, the single operating hand must move closer to the handle pivot point. However, such a position reduces the leverage available to deflect the energizing spring."

"It just made sense to put your body's weight and power over the exit area," Marks explained, then added, "A key issue is the kickback. If you push over the back, and the force comes out the front, the front jumps upward. But if your force is over the front, the kickback is prevented."

But there is more about human factors engineering to learn from Marks's stapler designs. He includes a feature he calls "passive release." The impact release mechanism is designed for very low friction and a correspondingly low release force. The result is a squeeze force that increases smoothly, with no noticeable step increase even at the release point.

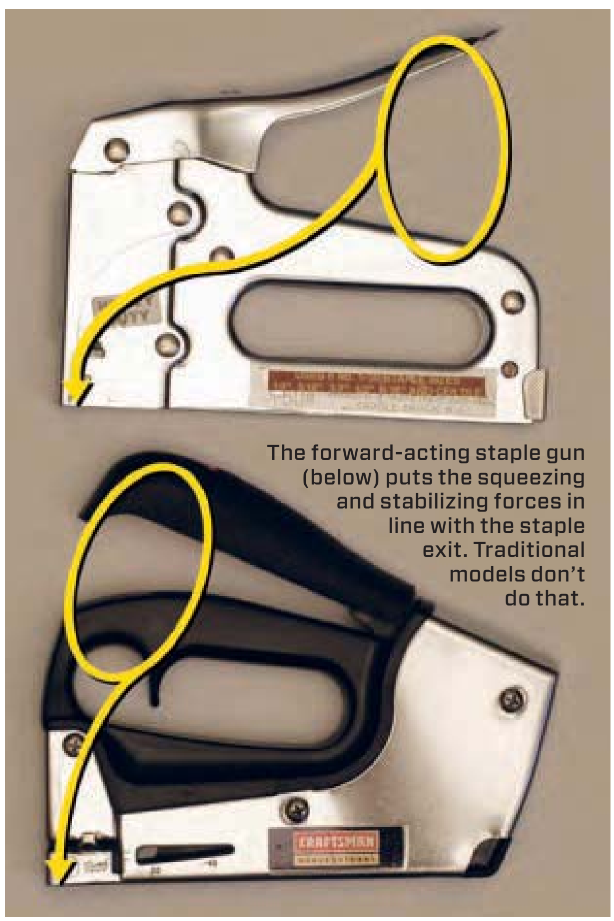
"It's got a light bias to move out of engagement, and it suddenly becomes free to move," Marks said. "Like with anything, including a mechanical or electrical device, you want the force on the trigger to be reasonably constant. If the spring action is too varied, the trigger won't be real predictable."

The two common styles of nutcrackers, lever and screw, are instructional due to their dissimilar mechanical human factors. In either case, one would think, the goal is to apply a suitable cracking force. Perhaps, but if you think of the shell as a stiff spring that will break with a definite strain, the goal is displacement. The reaction force for any strain is governed by the spring rate of the shell up to the break force.

With lever-style nutcrackers, which offer a suitable mechanical advantage for shelling nuts, resistance to motion is supplied entirely by the shell. Once the shell breaks, the resistance to motion largely disappears. But the force does not, with the result being crushed nut meats.

The screw-threads in screw-type nutcrackers provide a larger mechanical advantage than lever-type units have, and friction in the threads resists and arrests motion. The user inputs are quite different for the two nutcrackers. In the lever style, we input force until the shell breaks. In the screw style, we input motion. But the real difference, according to David Chastain, is in the stored energy. He said of the screw type, "All of the energy that's available is in the nut. It's compressing [the shell]. Once [the shell] cracks, the energy is gone. There's no more stored energy in the system."

But there is more to this example than shelling walnuts. "In applying forces to products in normal use, you have to think about what happens if there is some kind of unanticipated event," Chastain said. He said designers should ask, "Am I putting in more energy than I need?" Designers should further consider how that energy might be directed, he said. He likened it to cutting toward oneself. The lesson is that mechanical designers should know how much energy is going into a system, how much is being stored, and how it might be released.



The forward-acting staple gun (below) puts the squeezing and stabilizing forces in line with the staple exit. Traditional models don't do that.

Even cell phone texting offers a lesson in mechanical human factors. The obvious preferred method is to use one or both thumbs, but why? If thumbs were really faster than fingers, we would always type with thumbs, but we don't. Designers of cell phones may know the complete answer to why people text as they do, but the short, solid load path (thumb to fingers) for pushing the keys must be part of the answer. Robust stabilization—the device cradled in the fingers—must be another.

Human factors engineering may not yield a perfect solution, and usability testing may always be necessary. But by understanding and applying basic principles of human factors engineering throughout a project, designers can spare design iterations and establish a firm human factors foundation for their products. ■