
The Biomechanics of Prehension

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Key Words: hand function • occupational therapy • rehabilitation, hand

Occupational therapists who work with people who have physical dysfunctions are often involved in the treatment of hand injuries or disabilities. This article describes some of the mechanical principles that affect hand function, including kinematics, kinetics (force and torque), friction, stress, and strain. Practical occupational therapy examples are used to explain these principles.

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This article was accepted for publication December 15, 1988.

Good hand function depends on three components of the human anatomical system working properly: the muscle fibers must produce tension, or force; the bones, tendons, and ligaments must transmit this force; and the skin must indicate the point of force application (Brand, 1985). Several mechanical principles are operative during the smooth coordination of the force production, transmission, and application. The purpose of this paper is to describe some of these mechanical principles, including kinematics; kinetics; and friction, stress, and strain. Examples will be used to explain the transmission of muscle tension, the point of application, and the external stresses that affect hand movements. (For an explanation of muscle dynamics, which is beyond the scope of this article, see Brand, 1985. For an explanation of the actions of specific muscles, see Trombly & Cole, 1979, and Basmajian & DeLuca, 1985.)

The Mechanics of Movement

The mechanics of movement, called *dynamics*, consists of two components, kinematics and kinetics. *Kinematics* is the study of motion and is described in terms of displacement, velocity, and acceleration with respect to time. *Kinetics* is the study of the relationship between force, the mass of a body, and motion (Beer & Johnston, 1984).

Kinematics

The term *kinematics* describes the movement of a body or body part. *Displacement* is the position of a particle or a body in space. For example, consider a man walking down a trail. The man's displacement is his position on the path relative to some fixed point (e.g., 10 m to the west of a specific house). The pace at which the man walks (e.g., 1 m/s, going south) represents his *velocity*, which is the change in his position in a specific unit of time. In this case, the unit of time is 1 s. Velocity has both a quantity, or size, and a direction. If our hypothetical man on the path hears a dog growling behind him, his velocity may change. This change in velocity (probably an increase) is called *acceleration* and is a change relative to time. In this example, the acceleration would be measured in meters per second in each second (m/s^2). This example of the man walking on the trail demonstrates movement in a line. Not only can whole body movement, such as walking, be described in terms of linear kinematics (i.e., displacement, velocity, and acceleration), but individual body parts can also be described in these terms. For example, hand movement in both infants (Halverson, 1931) and adults (Bizzi & Abend, 1983) is usually straight or only gently curved. The

movement of the hand will thus be measured by linear kinematics.

Movement can also occur about a fixed point, or axis. If our hypothetical man's arms are swinging during his walk, his shoulder is swinging around a point in the shoulder joint. Therapists who measure range of motion are aware of this type of movement, which is called *angular movement*. A therapist places a goniometer over a joint, such as the metacarpophalangeal (MCP) joint of the thumb, to measure flexion of the joint. In the thumb, the position of the proximal phalanx may be at a 50° angle from the position of the metacarpal. This is the proximal phalanx's *angular displacement* relative to the metacarpal of the thumb, which for our purposes is measured in degrees. *Angular velocity* is the change in angular displacement with time (measured in degrees per second). For example, angular velocity would describe how quickly a person bends the fingers to make a fist. If the hand starts from a fully extended position, without moving, then gradually increases the velocity of the flexion, this is *angular acceleration* and is measured in degrees per second per second.

Kinetics

Force. In the clinic, occupational therapists work constantly with force. For example, they produce force at a joint by adding a flexion sling to a dynamic splint, thus encouraging an increased amount of flexion in the joint angle. Another example is when an occupational therapist uses force to place a hemiplegic person's arm in a shirtsleeve.

Force can be either a push or a pull and can be observed by the effect it has on the body on which it acts (Frankel & Burstein, 1970). Force is defined precisely by Newton's second law of motion, which states that Force = mass (kilograms) × acceleration (m/s²), which is abbreviated kg · m/s² (Atkins, 1970). The unit of measurement for force is the newton. As already noted, acceleration has both magnitude and direction. If a person holding a hammer accelerates the hand with the hammer downward toward a nail, the hammer will exert force on the nail. Because acceleration is related to force, force also has both magnitude and direction and is exerted in the same direction as the acceleration (Beer & Johnston, 1984).

Force is proportional to acceleration. If a karate expert's hand hits a block of wood very slowly, probably nothing will happen. This is because not enough force was applied. However, if the hand has a high acceleration and the movement is performed correctly, the resultant force will be great enough to break the block of wood.

More than one force may act on a body part at a time. For example, the tendons of both the flexor digitorum profundus and the extensor digitorum

communis muscles cross the distal interphalangeal (IP) joint of the middle finger and are attached to the distal phalanx. If the flexor digitorum profundus muscle contracts, the distal IP joint flexes. Conversely, if the extensor digitorum communis muscle contracts, the distal IP joint extends. Each muscle exerts force that causes movement in the direction of the pull. However, both muscles may pull at equal contraction levels with no resultant movement, as sometimes occurs in cocontraction. Because acceleration in this situation is equal to 0, no force is produced at the distal IP joint. Opposing the force of a muscle with the force of another muscle is one cause of movement inefficiency because the muscle that is trying to produce a force has to work harder to overcome the opposing muscle. This excessive cocontraction has been documented in persons with cerebral palsy who are unable to adequately relax antagonistic muscles (Winter, 1979). Inefficient muscle use and weakness resulting in reduced force output are also evident in persons with serious pain disorders, such as Sudeck atrophy (Omer, 1978).

Torque. Torque is the twisting or turning effect of a force (Frankel & Burstein, 1970). For example, to unscrew the lid of a jar, torque must be applied to turn it. Torque is exerted at a distance from the axis of movement. It is calculated with the equation Torque = force × distance. For human anatomy applications, the force in this equation refers to the tension that is produced by the muscle fibers and transmitted to the tendon. The distance in the equation is the perpendicular distance between the axis of rotation and the point of application of the force (Beer & Johnston, 1984). This distance is called the *force arm*, or *moment arm*. The *axis of rotation* is the point in the joint about which the joint rotates. A therapist attempts to place the axis of the goniometer at that point when measuring range of motion (Trombly, 1983). Therapists measure range of motion over the skin surface. In the finger and thumb joints, the axis of movement is actually in the distal end of the proximal bone of the joint (Brand, 1985).

To understand the importance of torque for the hand, consider the flexor pollicis longus tendon, which crosses both of the thumb joints. As the flexor pollicis longus muscle contracts, it produces force that causes flexion. This force is transmitted to the joint by the flexor tendon. Although the exact perpendicular distance between the axis of movement and the tendon is not known, Brand (1985) used some general distances and examples to describe torque.

The perpendicular distance from the tendon to the IP joint may be considered to be about 0.5 cm (see Figure 1). If the tendon applies a force of 3 N, then the torque across this joint will be 0.5 cm × 3 kg · m/s² = 1.5 N · cm.

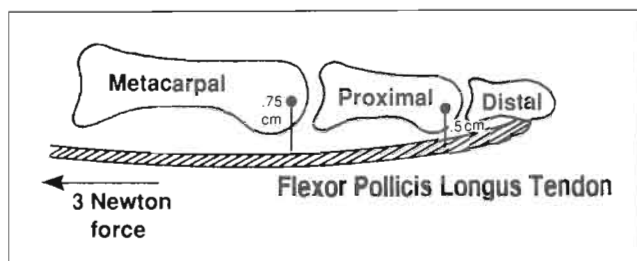


Figure 1. Torque produced at each joint of the thumb by the flexor pollicis longus tendon.

The same 3-N force that crosses the IP joint is applied across the MCP joint of the thumb. The distal end of the metacarpal bone is slightly larger than the distal end of the proximal phalanx of the thumb, so the perpendicular distance from the axis of the MCP joint to the tendon will be greater than that of the IP joint (approximately 0.75 cm). Because the perpendicular distance is greater, the torque produced will also be greater. In this case, torque is approximately 2.25 N·cm. The torque produced by the flexor digitorum profundus muscle would be even greater at the carpometacarpal joint. The muscle exerts the same tension, or force, on the tendon throughout the tendon's length. Thus, the effectiveness of that tendon at a specific joint is determined not by the muscle tension, but by the tendon's distance from the axis of movement. In the case of the flexor pollicis longus muscle of the thumb, the greatest torque is produced at the more proximal joint, because at this joint, the tendon is farthest from the axis of rotation.

This ratio of effectiveness, or torque, of a muscle at different joints cannot be altered. Tendons in the hand are kept close to the axis of movement by tendon sheaths. This provides a relatively constant distance between the tendon and the joint center and does not allow for bowstringing, or abnormal pulling of the tendon away from the joint (Brand, 1985). The adverse effect of torque, and its direction of pull, is evident in the fingers of persons who have rheumatoid arthritis or who have had a tendon pulley destroyed.

Other Mechanical Principles

Friction

Frictional forces develop when one surface moves against another (Beer & Johnston, 1976). These forces resist smooth movement. If a person pushes a block of wood along a horizontal surface of sandpaper, there is a frictional force between the two surfaces. Occupational therapists apply the concept of friction when they use rougher sandpaper to increase

the resistance against muscle strength during a purposeful activity.

A slippery, low-friction finish on tool handles requires an additional energy expenditure for tool retention. Coarse-textured tool handles can lead to skin irritation and diminished efficiency. Correct friction or texturing reduces the force required to grip the tool and permits most of the force to be transferred into the work (Meagher, 1987).

Many tasks in industry require gloves. The use of gloves affects both the sensory feedback from the hands and the frictional force between an object and the surface of the hands. Research testing the use of no gloves, one glove, or two gloves on each hand during a task indicated that one glove was superior to no glove or two gloves for force and torque production (Riley, Cochran, & Schanbacher, 1985). It is possible that the one-glove condition increased friction between the object and the hand or decreased feedback from sensations. Two gloves may have added too much bulk.

Normal synovial joints have a very effective lubricating system that acts to smooth the joint surfaces. When the joint moves, fluid is forced in to lubricate it. When the joint is immobile, the fluid within the joint capsule decreases. The area of cartilage that is under pressure stays that way, but the fluid is forced out. Therefore, human joints have the least amount of friction when they are moving (Barnett, Davies, & MacConaill, 1961).

If a joint has limited range because of tendon shortening, such as may occur in a person with spasticity or secondary to immobilization or soft tissue contractures in which the joint capsule and ligament are shortened, then it also has restricted function. Therapists may stretch the joint by means of serial casting or splinting (Fess & Philips, 1987). This does stretch the tissue; however, with the joint immobilized, risk of harming the joint capsule and lubrication system may increase. Brand (1985) recommended that joints that need immobilization be kept immobilized for 23 hours, but that active or passive movement of the joint occur for ½ hour or more one or two times a day to stimulate the synovial joint and reduce the chance of problems with the friction between the joint surfaces.

Diseases, such as rheumatoid arthritis, may impair the normal gliding, low-friction mechanism of synovial joints. These diseases can damage the joint, resulting in subluxation. Friction between the joint surfaces may be so great and the bone surfaces so damaged that the bones no longer glide at all, but rather tilt on one another (Brand, 1985). This causes the axis of movement to shift to the lip of the bone, thus altering the length of the force arm. The perpen-

dicular distance from the joint axis to the extensor tendon may decrease and the perpendicular distance to the flexor tendon may increase, giving the flexors a mechanical advantage.

The joint capsule in a rheumatoid joint may become so lax that the bones shift on one another, causing the axis to move from the dorsal aspect of the joint to the palmar surface. The force arm will be shortened in whichever direction the joint is attempting to move, and a zigzag deformity of consecutive joints may occur (Gerber & Hurwitz, 1986). In this case, an imbalance in resting forces and abnormal movement patterns and postures occur, and normal function is totally lost (Melvin, 1983).

Stresses and Strains

Occupational therapists affect solid structures within the body when treating the hand. Some of these structures (e.g., ligaments) are malleable, whereas others (e.g., bones) do not readily yield to external forces. An external force exerted on the hand will affect both the internal structures (the bones, ligaments, and tendons) and the point of force application (the skin).

Stress is the internal force per unit area that one part of the body exerts on another part. It is the result of the force, rather than the force itself (Frankel & Burstein, 1970). *Normal stress* acts perpendicular to the area under consideration. *Shear stress* acts parallel to the area under consideration.

Strain is the change in the configuration of the structure subjected to a stress (Fess & Philips, 1987). When forces act against one another in the body, they cause strain (Frankel & Burstein, 1970).

Tendons are subject to stresses from muscle contraction and to shearing forces from adjacent bones and ligaments; tendons become deformed as a result of these stresses. Armstrong, Fine, Goldstein, Lifshitz, & Silverstein (1987) extensively evaluated repetitive manual work tasks. They found that if a tendon is subjected to repetitive stresses, such as repetitive work requirements, the time between successive loads must be adequate for recovery. When work time is increased and recovery time is decreased, there is not sufficient time for recovery, and permanent injury occurs.

Shearing forces may also be transferred from tendons to adjacent nerves (Armstrong et al., 1987). This may occur during tenosynovitis, in which the tendon impinges on the adjacent nerve, resulting in nerve damage. Armstrong et al. concluded that repetitive and forceful manual tasks were associated with tenosynovitis, but that altering a job's design does not appear to alleviate this problem.

Transmission of External Forces

The hand is designed to do work (Brand, 1985). This means that forces are generated by both internal sources (the muscles) and external loads. When force is exerted at the tip of an outstretched finger, the torque produced by the finger flexors must be strong enough to overcome the external load if the finger flexes. Occupational therapists exert such an external force on the fingertips when they manually test the flexor digitorum profundus muscle. The therapist actually produces torque about the distal IP joint axis. The moment arm of the external force applied to the distal IP joint is measured along the distal phalanx, which is approximately 0.025 m long. If the therapist applies a 2-N force at the end of the fingertip, the torque caused by this external load will be $2\text{ N} \times 0.025\text{ m}$ or $0.05\text{ N}\cdot\text{m}$ at the distal IP joint (see Figure 2). At the proximal IP joint, the moment arm will be the length from the fingertip to the proximal IP joint, which may be approximately 0.06 m. Thus, at the proximal IP joint, the torque produced by the therapist will be $2\text{ N} \times 0.06\text{ m}$, or $0.12\text{ N}\cdot\text{m}$. It is obvious from these examples that the torque produced at the proximal IP joint is significantly greater than that at the distal IP joint.

To overcome the torque exerted by an external load, a patient must have greater muscle torque at the proximal joint than at the distal joint. Because the tendon of the flexor digitorum profundus muscle exerts the same force throughout its length and its perpendicular distance from each joint varies only slightly, it is not possible for the tendon to overcome the total external torque at the proximal IP joint. Other muscles, such as the flexor digitorum superficialis and the intrinsic muscles, assist the flexor digitorum profundus muscle in overcoming this torque (Brand, 1985). When the intrinsic muscles are weakened or paralyzed, balance in the musculoskeletal system is lost and severe disability may occur (Fess & Philips, 1987).

The shape and size of an object or tool handle affect the push or pull force the hand can exert.

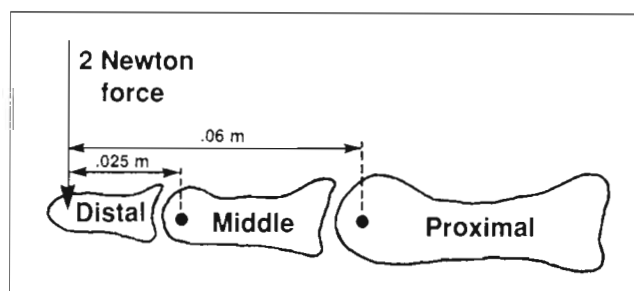


Figure 2. Torque produced by an external force at the fingertip.

Cochran and Riley (1986) extensively studied the effects of handle size and shape on the force exerted by the hand. They found that triangular handles were significantly better than circular handles and that square handles tended to have low force outputs. Rectangular and triangular handle shapes produced high force, whereas uniformly shaped handles, such as square and circular shapes, produced low force. Different handle shapes and sizes are preferred, depending on the activity, and in some cases, the gender of the user.

Most of the force generated by a muscle reaches its point of application. However, some of the force is absorbed by other structures along the way to the point of application. One reason for increased muscle force is abnormal friction within a joint. When a joint is unstable or diseased, some of the muscle's force may be needed to overcome the increased friction in the joint.

Point of Application

Occupational therapists are well aware of the problems that occur when insensitive skin is subjected to pressure. They teach persons who have sustained spinal cord injuries to move frequently, because a redistribution of weight reduces the area of pressure. They design and make splints to avoid pressure areas on the extremity (Fess & Philips, 1987). Pressure in the form of stress on the joints also can be damaging. *Pressure* can be defined as the area over which a force is applied. The long, smooth portions of splints exert low pressure because they apply force over a large area. However, the small edges of a splint or indentations in the splinting material can exert high pressure because they apply force over a very small area.

Brand (1985) suggested that normal skin sensitivity, rather than strength, may prevent people from performing daily tasks. For example, he stated that the small knobs used as switches on a light stand may be difficult to turn because the moment arm of the knob requires a large amount of pressure and shear stress.

Two aspects of sensation interfere with movement: a lack of sensation and too much sensation. Either of these will inhibit motor function in a person who has normal muscle strength. People who lack skin sensation (e.g., those with Hansen disease) need to be taught to compensate visually for this lack because they can experience skin breakdown. Brand (1985) suggested that it may be easier to teach these patients to use a large area of contact in performing tasks rather than to use less force.

Therapists teach persons to increase the contact area between the skin and containers such as jar lids to decrease the pressure on one area of skin. Hypersensitivity, or too much sensation (including pain),

may be very destructive, because the fear of producing pain prevents a person from exerting any force on the skin. This may cause muscle disuse and concomitant joint problems (Omer, 1978).

The incorrect application of finger slings or finger loops on hand splints might inadvertently add unwanted pressure. Finger loops should be placed at a 90° angle from the surface being placed in the loop to avoid unwanted pressure (Fess, Gettle, & Strickland, 1981). If splints are made inappropriately, increased pressure is created outside the joint on the surface of the finger. Resulting discomfort may cause the patient to choose not to wear the splint.

Conclusion

This paper has described some of the mechanical principles of hand movement. It is interesting that engineers, who understand mechanics and design robots, are only now turning to the dextrous human hand as a model for robotic hands because it is so well-suited for manipulative tasks (Becker & Thakor, 1988). Occupational therapists are not trained to design replacements for the human hand. However, their understanding of the principles of human movement places them in a unique position to help people with injured or disabled hands to resume purposeful, functional activities.

Acknowledgments

I thank S. M. Artzberger, J. J. McPherson, and M. L. Spitz for their helpful suggestions on the manuscript.

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