The unoperated hand: the role of passive forces in hand function after tetraplegia

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For the nonimpaired individual, hand function is a consequence of active muscle contractions orchestrated by the central nervous system. For example, thumb function is controlled by 10 distinct muscles. For most individuals with cervical spinal cord injury, none of the muscles controlling finger or thumb movement is controlled actively. As a result, passive forces must assume a critical role in functional use of the hand after tetraplegia.

An injury involving the cervical level of the spinal cord paralyzes muscles in the forearm and hand, with the degree of residual motor function traditionally linked to the segmental level of injury. In the unoperated tetraplegic upper extremity, an individual uses the hand to interact with the environment by combining residual voluntary control of proximal muscles and joints with the very small passive forces produced by finger and thumb muscles. Most rehabilitation modalities aimed at improving hand function after tetraplegia exploit the passive properties of the upper extremity. Many approaches, including the wrist-driven flexor hinge splint, surgical intervention, and functional electrical stimulation, attempt to strengthen the natural patterns of movement arising from the passive force-generating characteristics of the paralyzed hand muscles.

Passive tension produced by noncontracting structures is used most effectively for hand function by individuals who can extend the wrist after injury. If wrist extension is voluntary, a tenodesis grasp is possible [1]. The tenodesis grasp is a mechanism of hand opening and closing that arises from passive forces developed by the extrinsic muscles of the fingers and thumb during wrist extension and flexion (Fig. 1). A functional tenodesis grasp is most frequently observed in injuries below the fifth cervical segment, where brachioradialis and one or two of the radial wrist extensors are spared. Individuals who can voluntarily extend the wrist benefit from the tenodesis grasp even if they have paralyzed wrist flexors, because gravity can assist wrist flexion. Individuals with an effective tenodesis grasp are able to pick up light objects, such as finger food, and can often learn how to hold a utensil to eat, write, and brush their teeth [2]. Individuals who cannot extend the wrist are more dependent on assistance for many daily functions [3].

While the pinch force produced using a passive tenodesis grasp is minimal, some hand function is possible even in the unoperated hand. During the first postinjury year, the tenodesis grasp is the basis for hand movement. Generally, surgical reconstruction of the hand is not recommended until approximately 1 year after trauma to allow neurological recovery and physical and psychological stabilization [4]. During this period, the patient...
Overview

The tensile properties of the soft tissues surrounding a joint determine its resting posture and passive range of motion [6]. A joint’s resting posture is the position at which the tensile properties of the passive tissues, including ligaments, tendons, and inactive muscle, balance each other. That is, the net moment (or torque) at the joint is zero. As the joint is moved from its resting posture, the surrounding soft tissues deform and produce forces and moments that resist movement. For example, soft tissues, such as ligaments and inactive muscle–tendon units, produce force that increases with length. When the wrist is extended, the wrist flexors lengthen, producing passive forces that result in a net flexion moment at the wrist. In contrast, when the wrist is flexed, the wrist extensors produce a wrist extension moment (Fig. 2).

Because multiple tissues cross a single joint, it is difficult to discern how much each tissue contributes to a joint’s passive properties overall. This discussion focuses on the passive forces and moments produced by muscle–tendon units because of their importance to the tenodesis grasp.

The force a muscle produces depends on its length. The force-length relationship of muscle has active and passive components (Fig. 3) [7]. In the case of paralyzed muscle, only the passive component remains. According to the cross-bridge theory, the variation in active isometric force produced by a muscle at different fiber lengths is due to the sliding of myosin and actin filaments relative to each other, which influences the number of cross-bridges formed between the filaments within each sarcomere [8]. In contrast, passive force is thought to be due to connective tissue within the muscle and the elasticity of muscle fibers [7]. Muscle is thought to produce passive force when it reaches lengths longer than its optimal length (the length where the muscle produces its maximum active force). However, the length where passive force begins may vary across muscles [9].

A recent study suggests the maximum length a muscle reaches in vivo may better explain the onset of passive force production [10]. Regardless, once a muscle reaches the length where passive force develops, further lengthening increases the passive force produced.

Muscle force is applied to the skeleton through tendon, composed primarily of collagen. Generally tendon has some degree of elasticity. The passive force produced by a muscle–tendon unit depends on (1) the overall length of the fibers...
Passive forces produced by multiple muscle-tendon units crossing a joint are transformed to joint moments by way of their moment arms. The magnitude of the moment generated by a muscle-tendon unit about a joint axis is the product of its force and moment arm, which can be thought of as the shortest distance between the muscle-tendon path and the axis of rotation. The net joint moment is the sum of individual moments produced by the different muscles crossing a joint. The passive moment produced at a joint increases as the joint is moved towards the limits of its range of motion (see Fig. 2).

Because the extrinsic muscles of the fingers and thumb cross the wrist, the position of the wrist influences the passive properties of the finger and thumb joints [6]. When the wrist is extended, the passive forces produced by the extrinsic flexors generate passive moments at the joints of the fingers and thumb, as well as at the wrist. The moments produced at the finger and thumb joints move the hand into a closed or key pinch posture. If the thumb touches a rigid object, the thumb position stabilizes, and the passive thumb flexion moments are transmitted to the object as a force at the point of contact. Further wrist extension increases the passive moments, which increases the force applied to the object. Similarly, wrist flexion lengthens the extrinsic extensors, and the passive moments produced at the finger and thumb joints extend the digits and open the hand.

Passive joint properties of the hand and upper extremity can be exaggerated after cervical spinal cord injury [11]. The primary factor responsible for this change is unclear, but changes in muscle-tendon properties resulting from injury likely play a role. For example, muscles paralyzed at the lower-motor neuron level may produce larger passive forces because the muscle architecture is
considerably altered from normal (ie, it has more inelastic fibrous tissue and less elastic muscle fiber. In some respects, increased passive properties can be beneficial, because they may augment the pinch force produced by the tenodesis grasp. However, the larger passive moments produced after tetraplegia imply that a larger moment is required to move the joint. The active wrist extension moment required to balance the net passive flexion moment is larger for the individual with C4-level tetraplegia compared with the nonimpaired individual (see Fig. 2). In the extreme case, excessive passive force limits joint range of motion and the ability to produce a movement. This point is already recognized in the surgical community: joint contracture results from a pathological level of passive force and contraindicates surgical restoration of hand function after tetraplegia [5].

Posture, movement, and function in the unoperated hand

Posture

Key pinch has been described as the primary hand function to restore to individuals with tetraplegia [12]. The posture for key pinch is a natural position resulting from wrist extension in the non-impaired hand (see Fig. 1A). In the absence of voluntary muscle control in the hand to grasp or release an object, the resting posture of the fingers and thumb are critical to achieving an effective key pinch. Basically, the thumb pad should contact the lateral side of the index finger. Normally, the finger posture is a “cascade” resulting from a similar degree of flexion at the metacarpal-phalangeal (MP), proximal interphalangeal (PIP), and distal interphalangeal (DIP) finger joints. Of particular importance is the posture of the index finger, which provides a stable base to oppose the force produced by the thumb. The natural position of the thumb should approximate the middle phalanx of the index finger. However, individual differences in passive joint properties influence the key pinch posture that can be achieved.

Variations in resting hand posture observed in individuals with tetraplegia result from differences in specific muscle-tendon properties (described above) and other factors, such as scar tissue, adhesions, spasticity, and muscle imbalance, that influence joint properties [13]. Improper alignment of the fingers and thumb can interfere greatly with using the unoperated hand effectively and with the outcome of treatment to restore function.

For example, tightness (or increased stiffness) of the extrinsic finger flexors may be asymmetrical so that selected fingers are inappropriately positioned during grip. Excessive finger flexion may position the hand in a fist during attempted pinch, which can result in the thumb opposing the dorsal surface of the fingers instead of the lateral side of the index finger. Muscle imbalance caused by the loss of intrinsic musculature results in excessive PIP and DIP flexion and inadequate MP flexion, commonly referred to as a claw deformity (Fig. 4). These postural deficits can make it more difficult to hold even light objects.

Because of the importance of achieving a practical resting hand posture, temporary use of orthotics and splinting is advised often to preserve flexibility and positioning of the thumb and fingers [5]. Combined with passive movement therapies, braces and splints can enhance the effectiveness of the tenodesis grasp because they address basic positioning issues [14]. Preventing claw-hand posturing, proximal interphalangeal joint contracture, and thumb adduction contracture is particularly important [5]. Orthotic devices are designed to encourage shortening of the extrinsic finger and thumb muscles, to adjust the length of the adductor pollicis so the thumb contacts the lateral side of the index finger, and to prevent excessive carpometacarpal or metacarpal-phalangeal stiffness [14].

Although poor hand posture often limits function, sometimes individuals adapt to a suboptimal key pinch or closed hand posture. Motivated patients modify the manner in which they secure objects, ignoring the cosmetic appearance of performing a task if it provides them some ability to use their hands (Fig. 5).

Fig. 4. Muscle imbalance or contracture alters the basic lateral pinch posture and can interfere with function, as in this example of claw deformity. (Courtesy of V.R. Hentz, MD, Palo Alto, CA.)
Movement and function

The lack of a natural tenodesis grasp has been reported to interfere with function even in the post-operative hand [15]. Wrist extension strength is an important determinant of the effectiveness of tenodesis grasp. Because of the weight of the hand, the rest position of the wrist against gravity is in flexion. To produce an effective tenodesis grasp, the wrist extensors must have enough strength to overcome the wrist flexion moment imposed by the weight of the hand and the passive joint moments produced by muscles and joint structures crossing the wrist. As the wrist becomes more extended, the passive wrist flexion moment produced by muscles crossing the wrist increases (see Fig. 2). While this is the underlying mechanism of successful tenodesis (the increased wrist flexion moment results from the same passive forces that are flexing the fingers and thumb), it requires more strength to achieve more wrist extension. Extremely tight muscles could limit use of the tenodesis grasp if the wrist extensors cannot move the hand into an extended posture. In addition, the weight of an object imposes a wrist flexion moment that must be balanced to maintain a particular wrist position. Strong wrist extensors are required to maximize active wrist motion and provide the ability to hold objects in the hand.

The pinch force produced by the tenodesis grasp in the unoperated hand is extremely small and may be indistinguishable from zero force using standard clinical pinch meters [16–19]. Using a sophisticated force transducer that distinguishes forces as low as 0.02 N, we measured pinch forces produced using a tenodesis grasp from individuals with C5-level (complete) and documented the change in lateral pinch force that occurs as a function of wrist position (Fig. 6). The magnitude of this force (maximum force 1–2 N in the individuals we studied) is comparable to measurements of passive forces reported in studies of nonimpaired subjects [6] and laboratory investigations using cadaveric specimens [20].

Pinch forces as low as 2 N are ineffective for many daily activities. As part of a larger study conducted at the VA Palo Alto Health Care System, the minimum pinch force magnitude and grasp opening required to accomplish five simple tasks were quantified. All of the tasks required lateral pinch, including: opening and closing a zipper; stabbing food with a fork; pressing a remote control button; inserting and removing a plug from a socket; and inserting and removing a key from a lock. Forces greater than 2 N were necessary to accomplish these tasks, with the exception of pressing the remote control button [21]. The subject whose pinch force data appear in Fig. 6 was unable to perform any task, except for pushing the remote control button, without using compensatory strategies. The diminished force range and delay in force production limit the tasks that can be performed independently and the ability to secure objects in the hand.

A nonsurgical option for enhancing the tenodesis effect of the paralyzed hand is the wrist-driven flexor hinge splint for functional pinch [22]. The splint maintains the thumb in a fixed position and guides the finger flexion that occurs with wrist extension. Rather than a key pinch, the flexor hinge splint provides a “three jaw chuck” pinch, where the tips of the index and long fingers contact
Wrist extension angle (°)

Fig. 6. Lateral pinch force as a function of wrist extension angle, measured in an individual with C5 complete tetraplegia at a narrow grasp opening. Force increased with increasing wrist extension, reaching a peak force of 1.9 N at 77° wrist extension.

the tip of the thumb. Wrist flexion extends the fingers, opening the hand. The splint is useful during the first postinjury year to provide a functional pinch and the opportunity to learn to use the wrist to control finger and thumb position. Surgical duplication of the splint function requires fusing the thumb and fingers in the position maintained by the splint. Surgery fixes the posture of the hand for the three jaw chuck pinch, but it may interfere with other tasks, such as dressing and pushing a wheelchair.

Surgical enhancement of natural tenodesis

The relationship between pinch force and wrist extension—the basis of passive tenodesis grasp in the unoperated hand—exists after functional restoration of grasp. Moberg is credited with focusing the goal of surgery for most tetraplegic patients on augmenting the natural adaptation to injury with a technically simple (and theoretically reversible) surgical procedure. The Moberg procedure increases the pinch force produced by the natural tenodesis grasp by surgically anchoring the flexor pollicis longus (FPL) to the radius [12]. The outcome exhibits an increase in lateral pinch force related to wrist position [15]. Memberg and Crago observed that pinch force increased from 3.3 N to 6.0 N with wrist extension in a subject with C5/C6-level quadriplegia whose grasp/release abilities were restored through the use of functional neuromuscular stimulation (FNS) [23]. Referring to the surgical procedure as “tenodesis” and its outcome as “tenodesis grasp” presents a possible source of confusion. Following FPL tenodesis described by Moberg, any increase in pinch force relative to the preoperative level depends entirely on movement of more proximal joints. The characteristics of the passive force generated by FPL differ substantially between preoperative and postoperative states. For example, ignoring the variables mentioned above, (scar tissue, adhesions, etc), preoperative passive force produced by FPL depends on muscle properties, particularly connective tissue within the muscle and elasticity of muscle fibers. However, the force it produces postoperatively results primarily from the length at which the tendon is anchored. Because passive force has been enhanced surgically, a reduced range of wrist extension in the postoperative patient is observed often, since the system now works about a relatively rigid tendon instead of a more or less elastic muscle. In contrast, although unoperated tetraplegic patients demonstrate a degree of FPL “tightness,” usually it does not limit the patient’s active range of wrist extension.

If the strength of the wrist extensors is sufficient, the postoperative wrist extension range increases, presumably as a consequence of lengthening the anchored FPL tendon, changes in pulley lengths, or elongation of the scar between tendon and bone. Expecting this lengthening, many surgeons “set” the initial FPL length somewhat shorter than ideal. All tenodesis operations require
an absolute period of postoperative protection from any stress (Moberg recommends 4 weeks) and variable periods of protection from great stress (eg, weight bearing).

Compensatory strategies/adaptations

Individuals with tetraplegia develop compensatory strategies to maximize use of their hands. Most individuals develop alternative methods for performing daily tasks. One technique is to take advantage of the effect of gravity to augment grasp function. This adaptation is built into the tenodesis grasp because gravity-assisted wrist flexion is often the only means of opening the hand. Similarly, forearm supination allows an individual without wrist extension and a tenodesis grasp to cradle or balance objects in the hand. Initially the object is positioned in the hand by passively extending the fingers against the object or a table surface. Then the forearm is supinated, allowing gravity to extend the wrist and secure the object in the hand. Similarly, external rotation of the humerus can provide elbow extension passively.

The difficulty with compensatory strategies is that the extremity may not be in a functional posture and repositioning the hand loses the positive effects of gravity. For example, if one uses gravity to achieve wrist flexion, the wrist can flex only in arm postures where gravity assists wrist flexion, making adaptation far less robust than wrist flexion provided by active control of the wrist flexors. The grasp or pinch force produced using compensatory strategies is minimally adequate to retain the object in the hand, but often not sufficient to resist external forces applied to the object. For example, a tenodesis grasp may be used to pick up a key from a table and align it with the lock, but inserting the key and turning it are impossible.

Another strategy employed by individuals with tetraplegia is to produce active moments at proximal joints and use the hand to impart the resulting forces on a stationary object. This adaptation can be observed in a variety of tasks, such as pushing a key into a lock or a plug into a wall socket using the base of the hand. We quantified this effect in our laboratory by asking subjects to produce target force levels against rigidly mounted force sensors (Fig. 7). We provided the subject with feedback about the forces produced by the thumb and index finger separately, and we monitored elbow and wrist position. As expected from the tenodesis function, extending the wrist is the strategy to increase thumbtip force toward the target force. In the absence of active finger abduction, the index finger exerted higher forces than the thumb because the subject produced an active elbow flexion moment, which was transmitted as a force to the stationary testing device. This compensatory action likely augments pinch force during functional tasks involving fixed structures, such as pushing a key into a lock. It is impossible to summarize all the methods of accomplishing important functional tasks devised by individuals with cervical spinal cord injury. It is sufficient to say these individuals are ingenious in finding ways to use every resource available.

Summary

Passive forces play a large role in hand function after tetraplegia. Most individuals with tetraplegia choose not to undergo surgical reconstruction of hand function and, therefore, depend on the passive properties of their musculoskeletal system to perform functional tasks. Knowledge of the levels of force needed to perform many of these tasks is lacking. Understanding the mechanics of producing passive force is important for designing adaptive tools and other devices for tetraplegic individuals.

Knowledge of the passive properties of the upper extremity is important in forming treatment strategies. The passive forces produced for change to the tenodesis grasp are small but useful to the individual. Since these forces arise from basic anatomy and muscle function, they are important even
after surgical restoration of hand function. Compensatory strategies for the unoperated hand probably play a role in the operated hand. The approach to surgical restoration of grasp must consider how passive forces contribute to functional outcome.

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