

The Anatomy and Mechanics of the Human Hand

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It is obvious to all that the human hand represents a mechanism of the most intricate fashioning and one of great complexity and utility. But beyond this it is intimately correlated with the brain, both in the evolution of the species and in the development of the individual. Hence, to a degree we "think" and "feel" with our hands, and, in turn, our hands contribute to the mental processes of thought and feeling.

In any mechanism, animate or inanimate, functional capabilities relate both to structural characteristics and to the nature of the control system available for management of functions singly or in multiple combinations. Just so with the human hand. Analysis of normal hand characteristics therefore requires an understanding of both sensory and mechanical features. Of course whole volumes have been written on hand anatomy, and it is not possible in a short article to describe all elements in detail. It is helpful, however, to review the basic construction of bones and joints and of the neuromuscular apparatus for governing motions and forces. Twenty-four muscle groups, controlled by the various motor and sensory nerve pathways, with their rich potentialities for central connection, and acting upon a bone and joint system of great mechan-

ical possibilities, give to the hand its capacity for innumerable patterns of action.

THE FUNCTIONAL STRUCTURE OF THE HAND THE BONES

The bones of the hand, shown in Figure 1, naturally group themselves into the carpus, comprising eight bones which make up the wrist and root of the hand, and the digits, each composed of its metacarpal and phalangeal segments (Table 1). The carpal bones are

Table 1
BONES AND JOINTS OF THE HAND AND WRIST

Carpal bones	
GM,	Greater multangular
N,	Navicular
L,	Lunate
T,	Triquetrum
P,	Pisiform
LM,	Lesser multangular
C,	Capitate
H,	Hamate
Metacarpal bones	
M-I,	II, III, IV, V
First phalangeal series	
FP-I,	II, III, IV, V
Second phalangeal series	
SP-II,	III, IV, V
Third phalangeal series	
TP-I,	II, III, IV, V
Joints	
RC,	Radiocarpal
IC,	Intercarpal
CM,	Carpometacarpal
MP,	Metacarpophalangeal
PIP,	Proximal interphalangeal
DIP,	Distal interphalangeal

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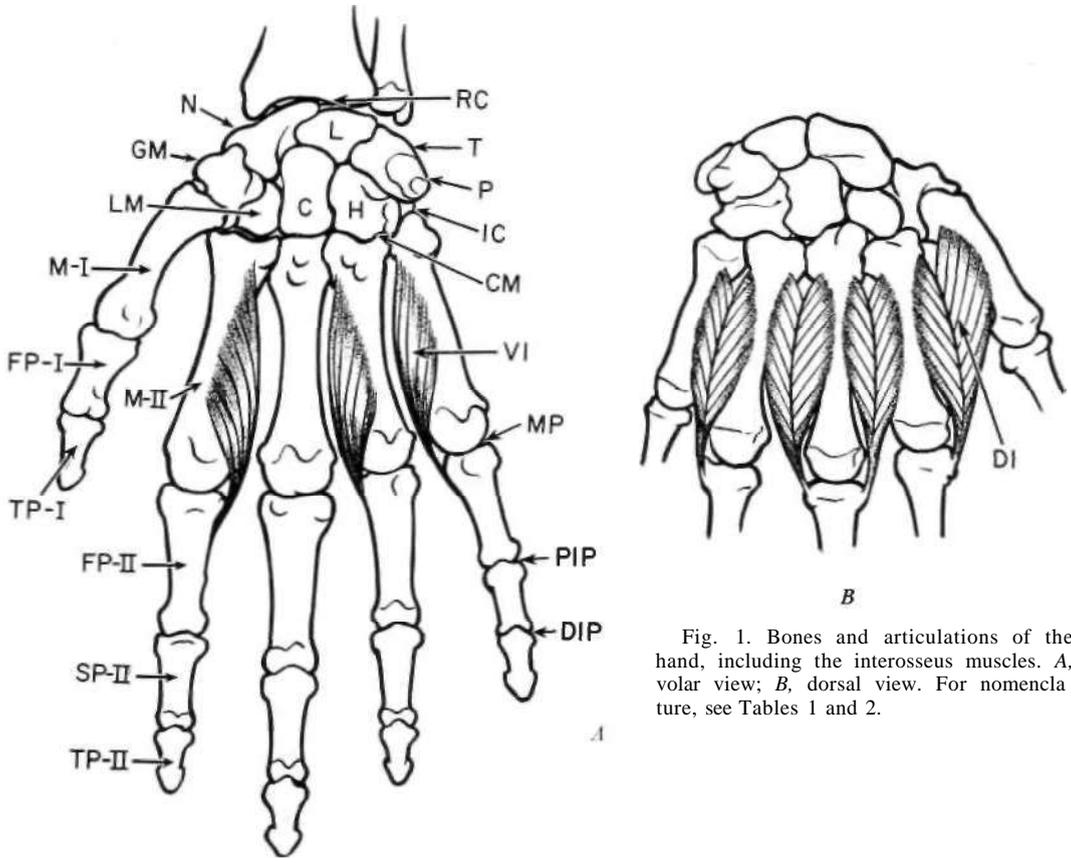


Fig. 1. Bones and articulations of the hand, including the interosseus muscles. *A*, volar view; *B*, dorsal view. For nomenclature, see Tables 1 and 2.

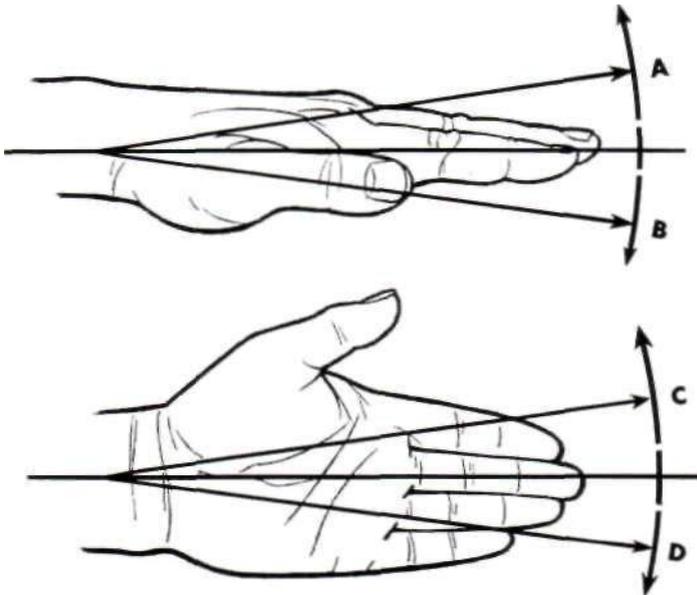


Fig. 2. Angles of rotation about the wrist. *A*, extension (or dorsiflexion); *B*, flexion (or volar flexion); *C*, radial flexion; *D*, ulnar flexion.

arranged in two rows, those in the more proximal row articulating with radius and ulna. Between the two is the intercarpal articulation. The bony conformation and ligamentous attachments are such as to prevent both lateral and dorsal-volar translations but to allow participation in the major wrist motions (Fig. 2).

In each of the digits, the anatomical design is essentially the same, with exceptions in the thumb. Metacarpals II through V articulate so closely with the adjacent carpal bones of the distal row that, although they are capable of some flexion and extension, independence of motion is very limited. The metacarpal shafts are arched to form the palm, and the distal ends are almost hemispherical to receive the concave curvature of the proximal ends of the first phalanges.

The metacarpophalangeal joint exhibits a pattern seen also in the interphalangeal joints. As shown schematically in Figure 3, the virtual center of rotation lies approximately at the center of curvature of the distal end of the proximal member. The lateral aspects of the joint surfaces are narrowed and closely bound with ligaments, so that lateral rotation is small in the metacarpophalangeal joints and lacking entirely in the phalangeal articulations. Hence, the latter are typical hinge joints. The thumb differs from the other digits first in that the second phalanx is missing and, second, in that there is greater mobility in the carpometacarpal articulation.

MUSCLES AND TENDONS

Most of the muscles of hand and wrist

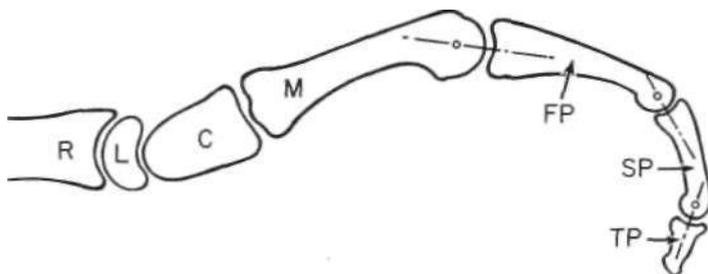


Fig. 3. Section through radius, lunate, capitate, and the bony structure of digit III, showing virtual centers of rotation of each segment upon the next more proximal one. When the fist is clenched, the prominence of the knuckles is formed by the head of the more proximal member of each articulation. For nomenclature, see Table 1.

Table 2
MUSCLES OF THE HAND AND WRIST

ADQ,	Abductor digiti quinti
AP,	Adductor pollicis
APB,	Abductor pollicis brevis
APL,	Adductor pollicis longus
APQ,	Adductor pollicis obliquus
APT,	Adductor pollicis transversus
DI,	Dorsal interosseus
ECRB,	Extensor carpi radialis brevis
ECRL,	Extensor carpi radialis longus
ECU,	Extensor carpi ulnaris
EDC,	Extensor digitorum communis
EDQP,	Extensor digiti quinti proprius
EIP,	Extensor indicis proprius
EPB,	Extensor pollicis brevis
EPL,	Extensor pollicis longus
FCR,	Flexor carpi radialis
FCU,	Flexor carpi ulnaris
FDP,	Flexor digitorum profundus
FDQB,	Flexor digiti quinti brevis
FDS,	Flexor digitorum sublimis
FPB,	Flexor pollicis brevis
FPL,	Flexor pollicis longus
I,	Interosseus
L,	Lumbricalis
ODQ,	Opponens digiti quinti
OP,	Opponens pollicis
PL,	Palmaris longus
VI,	Volar interosseus

(Table 2) lie in the forearm and, narrowing into tendons, traverse the wrist to reach insertions in the bony or ligamentous components of the hand. Generally, the flexors (Fig. 4) arise from the medial epicondyle of the humerus, or from adjacent and volar aspects of the radius and ulna, and then course down the inside of the forearm. They are, therefore, in part supinators of the forearm (Fig. 5). The extensors (Fig. 6) of wrist and digits originate from the lateral epicondyle and parts of the ulna, pass down the dorsal side of the forearm, and thus assist in pronation. The thumb shares in the general flexor-extensor scheme, but its extensors and abductors originate from mid- and distal parts of radius and ulna.

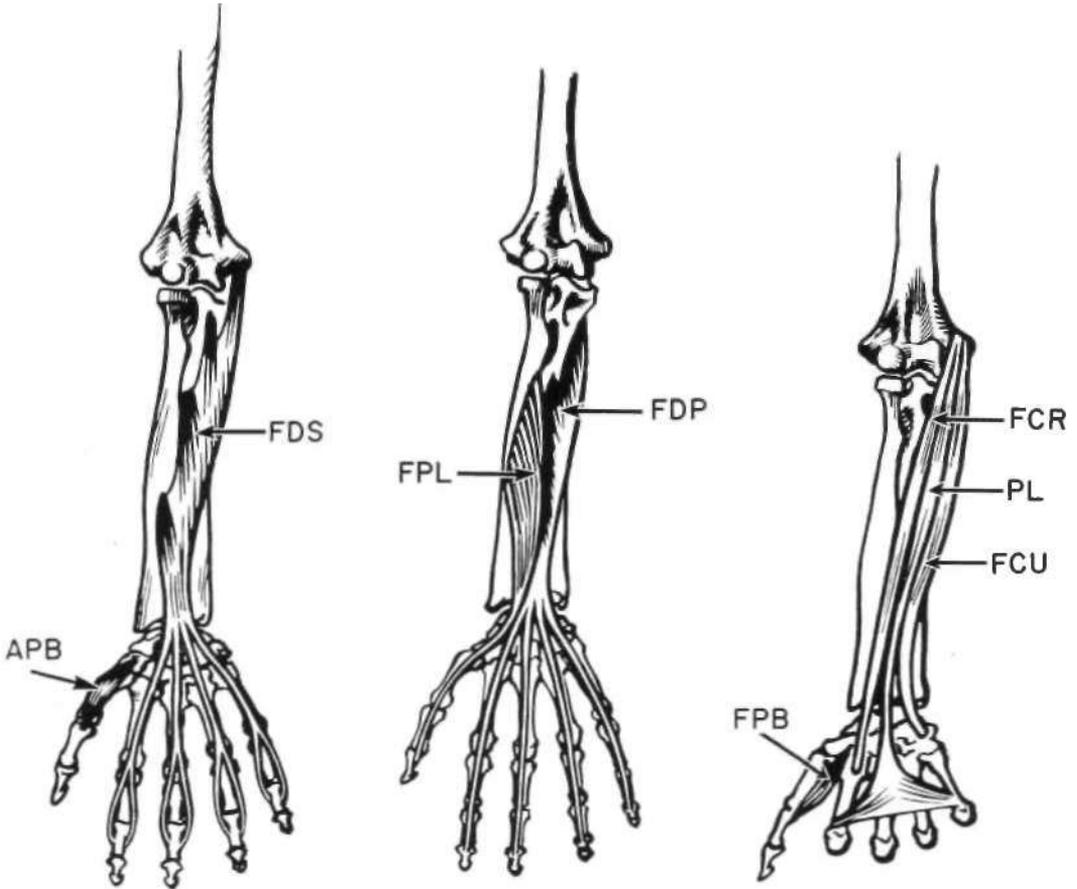


Fig. 4. Flexors of wrist and digits. For nomenclature, see Table 2.

The tendons of wrist and hand pass through bony and ligamentous guide systems, as shown schematically in Figure 7. Flexor tendons pass through a "tunnel" bounded dorsally by carpal bones, laterally by the greater multangular and the projection of the hamate, and volarly by the tough transverse carpal ligament. Similarly, the dorsal carpal ligament guides the extensor tendons, and a system of sheaths serves as a guide for flexor and extensor tendons through the metacarpal and phalangeal regions.

The intrinsic muscles of the hand, *i.e.*, those with both origin and insertion confined to wrist and hand (Fig. 8), are, with the exception of the abductors of thumb and little

finger, specialized for the adduction of the digits and for opposition patterns such as making a fist, spherical grasp, and so on.

THE PALMAR AND DIGITAL PADS

The volar aspect of the palm and digits is covered with copious subcutaneous fat and a relatively thick skin so designed in a series of folds that it is capable of bending in prehension. The folds are disposed in such a way as to make for security of grasp, while the underlying fat furnishes padding for greater firmness in holding. Because, however, slipping of the skin over the subcutaneous fat would lead to insecure prehension, the folds are tightly bound down to the skeletal elements, much as mat-

tresses and upholstered furniture are quilted or otherwise fastened to prevent slippage of the filler.

In the hand, the volar skin is tied down by white fibrillar tissue connecting the sheaths of the flexor tendons to the deep layer of the dermis along the lateral and lower edges of the palmar fascia. The folds therefore vary with

the relative lengths of the metacarpal bones and with the mutual relations of the sheaths of the tendons and the edge of the palmar fascia.

The sulci, or furrows, are emphasized because the subcutaneous fat in any given area is restricted to the interval between the lines along which the skin is tied down. Thus pressure upon any individual monticulus cannot displace the underlying soft tissue beyond the boundaries established by the fibrillar connections. The relative size of any particular eminence is an indication of the size of the muscle involved and of its relative development through usage, with the exception that the size of the hypothenar eminence depends in part upon the prominence of the pisiform.

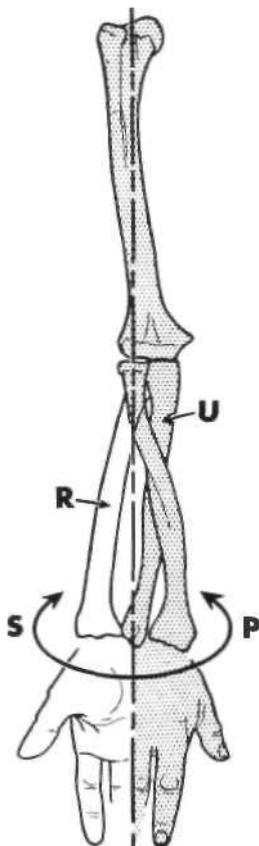


Fig. 5. Forearm design as related to hand mobility. By virtue of this arrangement, the hand can be rotated through 180 deg., palm up to palm down, with the elbow flexed. With the arm fully extended, participation of shoulder and elbow allows the hand to be rotated through almost 360 deg., palm up to palm up. *U*, ulna; *R*, radius; *P*, pronation; *S*, supination.

THE DORSAL INTEGUMENT

Unlike the volar surface, the dorsal side of the hand is covered with thin, soft, pliable skin and equally mobile subcutaneous tissue, both capable of yielding easily under tension. Because in flexion of the fingers and in making a fist the covering on the back of the hand must be able to stretch from wrist to fingernails, the dorsal skin is arranged in numerous minute redundancies, which, in the fiat-of-hand, are manifest in the typical transverse wrinkles, particularly over the phalangeal articulations. Special adaptations in the dorsal skin of the thumb accommodate the distinctive rotational planes of that digit about its carpometacarpal articulation. In the normal, healthy hand, the degree of redundancy in any given area is just such that all wrinkles are dispatched when the fist is clenched. Swelling in any area, dorsal or volar, inhibits flexion-extension of the part affected.

NERVE AND BLOOD SUPPLY

Three principal nerves serve the muscles of the hand (Fig. 9). Nerve supply is indicated, except for minor variations and exceptions, in Table 3. Each of these major nerve trunks diverges into countless smaller branches ending in the papillae of the palmar pads and dorsal skin, and the whole neuromuscular system is so coordinated in the brain that motor response to stimuli is ordinarily subconscious and reflex. Thus an object slipping from the grasp is automatically gripped more firmly, but not so firmly as to damage the hand itself. Noxious stimuli are rejected automatically, as when

Table 3
PRINCIPAL NERVES SERVING HAND AND WRIST FUNCTIONS

Nerve	Muscles Served
Radial	Extensors of wrist, thumb, and fingers.
Median	Flexors of wrist and fingers; abductors, opponens, and flexors of thumb; lumbricals I and II.
Ulnar	All other intrinsic muscles of the hand, including all interossei; lumbricals III and IV.

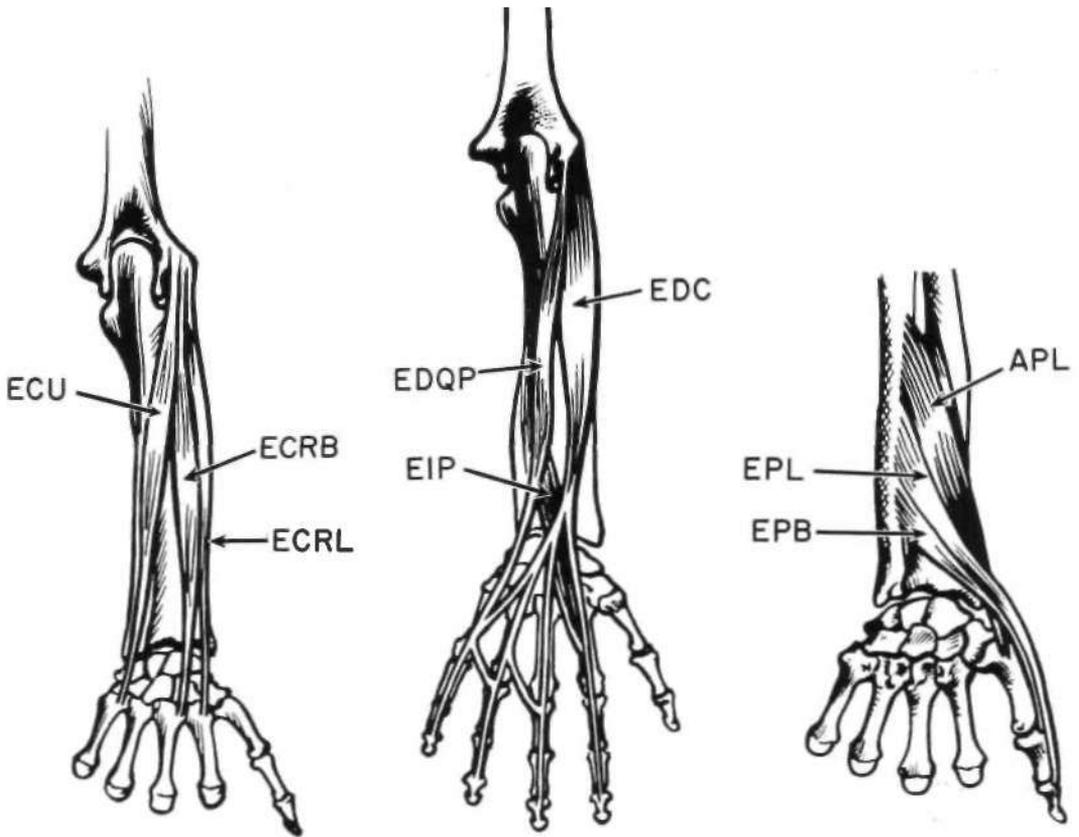


Fig. 6. Extensors of wrist and digits. For nomenclature, see Table 2.

the fingers are withdrawn from an object uncomfortably hot.

The wrist and hand receive their blood supply from the radial and ulnar arteries, which run parallel with the bones concerned, enter the hand through the flexor "tunnel," and then join through a double-arch system (Fig. 10). Small branches from the arches serve the digits. The major venous system comprises the basilic and cephalic veins superficially placed on the volar surface of the forearm.

THE RESTING HAND PATTERN

The resting hand assumes a characteristic posture, a feature easily seen when the hand hangs loosely at the side. The resting wrist takes a mid-position in which, with respect to the extended forearm axis, it is dorsiflexed

35 deg. (Fig. 11). It is worth noting that this is the position of greatest prehensile force (Fig. 12, bottom). The mid-position for radial or ulnar flexion appears to be such that the metacarpophalangeal joint center of digit III lies in the extended sagittal plane of the wrist (Fig. 11).

Typically, the conformation of fingers and thumb is similar to that shown for palmar prehension (Fig. 13), the fingers being more and more flexed from index to little finger. The relations between thumb, palm, and fingers are such as to permit grasp of a 1.75-in. cylinder crossing the palm at about 45 deg. to the radioulnar axis. Bunnell (4) considers this "an ancestral position ready for grasping limbs, weapons, or other creatures."

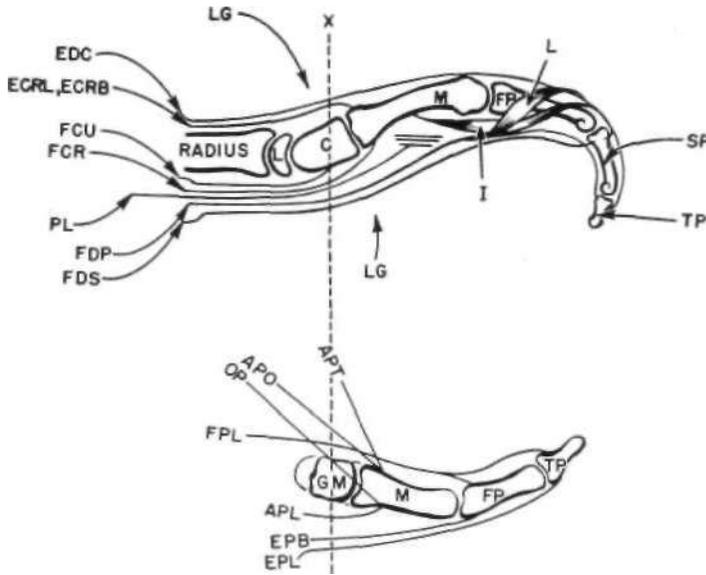


Fig. 7. The anatomy of prehension. Schematic sections through digits I and III show essential relations of muscles and bones. The letters *LG* indicate the presence of ligamentous guides which channel close to the wrist the tendons of muscles originating in the forearm. Guide line X—X indicates relative position of carpal bases of thumb and fingers. For rest of nomenclature, see Tables 1 and 2. From Taylor (12).

FIXED HAND ADAPTATIONS

In thrusting or striking actions and the like, the hand may assume fixed and rigid postures while functioning with the arm in support. These represent nonspecialized functions in which the hand serves merely as an adapted "end of the arm." The various forms include the flat-of-hand, the clenched fist, the knuckle and digital support postures, and so on.

WRIST MECHANICS

The wrist joint, composed of the radiocarpal and intercarpal articulations (Fig. 1), has an elliptical rotation field with the major axis in the dorsal-volar excursion, the minor in the ulnar-radial. No significant torsion occurs. Bunnell (4) gives the angular excursions about the radiocarpal and intercarpal articulation as shown in Table 4.

The rotation within the carpal bones during these movements is too complicated for brief treatment. Not only do the rotations occur at several articulating surfaces, but the virtual axes of rotation lie distal to the contact surfaces owing to gliding motions in the convex-concave structure of the joints. Idealization of the motions into those of a simple lever, ro-

tating about a fixed center, as implied in diagrams such as Figure 2, can be justified only as a convenient approximation.

The muscles traversing the wrist include those inserting into the carpus and metacarpus and those mediating flexion and extension of

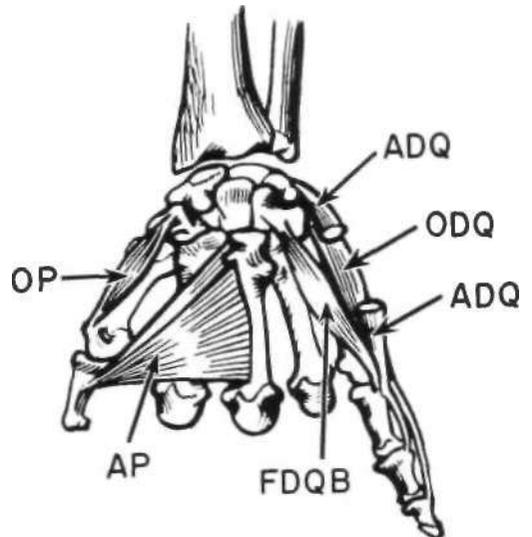


Fig. 8. Volar intrinsic muscles of the hand. For nomenclature, see Table 2.

the phalanges. The latter contribute to the wrist action, particularly under loads. In such cases, the finger muscles develop reaction against the object held (or within the hand itself if the fist is clenched) and add their forces to wrist action. The forces, action, and grouping of these muscles are given in Table 5.

PREHENSION PATTERNS

It is evident equally from a study of the muscle-bone-joint anatomy and from observation of the postures and motions of the hand that an infinite variety of prehension patterns is possible. For purposes of analysis, however, it suffices to describe the principal types. Seeking a logical basis for defining the major prehension patterns, Keller et al. (9) found that the object-contact pattern furnishes a satisfactory basis for classification. From

photographic observation of the prehension patterns naturally assumed by individuals when (a) picking up and (b) holding for use

Table 4
ANGULAR EXTENT OF WRIST FLEXIONS^a

Articulation	Dorsal Flexion (deg.)	Volar Flexion (deg.)	Total (deg.)	Ulnar Flexion (deg.)	Radial Flexion (deg.)	Total (deg.)
Capitate-radius	78	44	122	28	17	45
Capitate-lunate.	34	22	56	15 ^b	8 ^b	23 ^b
Lunate-radius	44	22	66	13 ^c	9 ^c	22 ^c

^a From Bunnell (4).

^b Between capitate and proximal carpal row.

^c By difference.

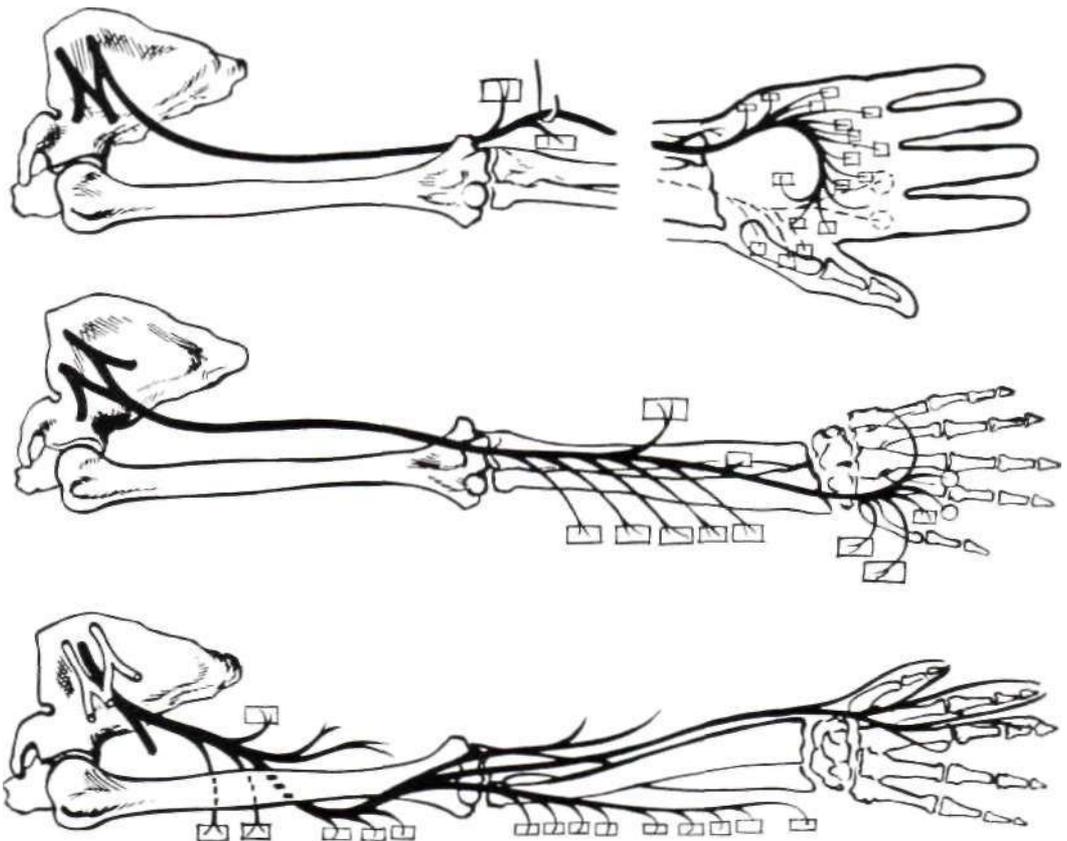


Fig. 9. Nerves supplying the hand. Top to bottom, ulnar nerve, median nerve, radial nerve. See Table 3.

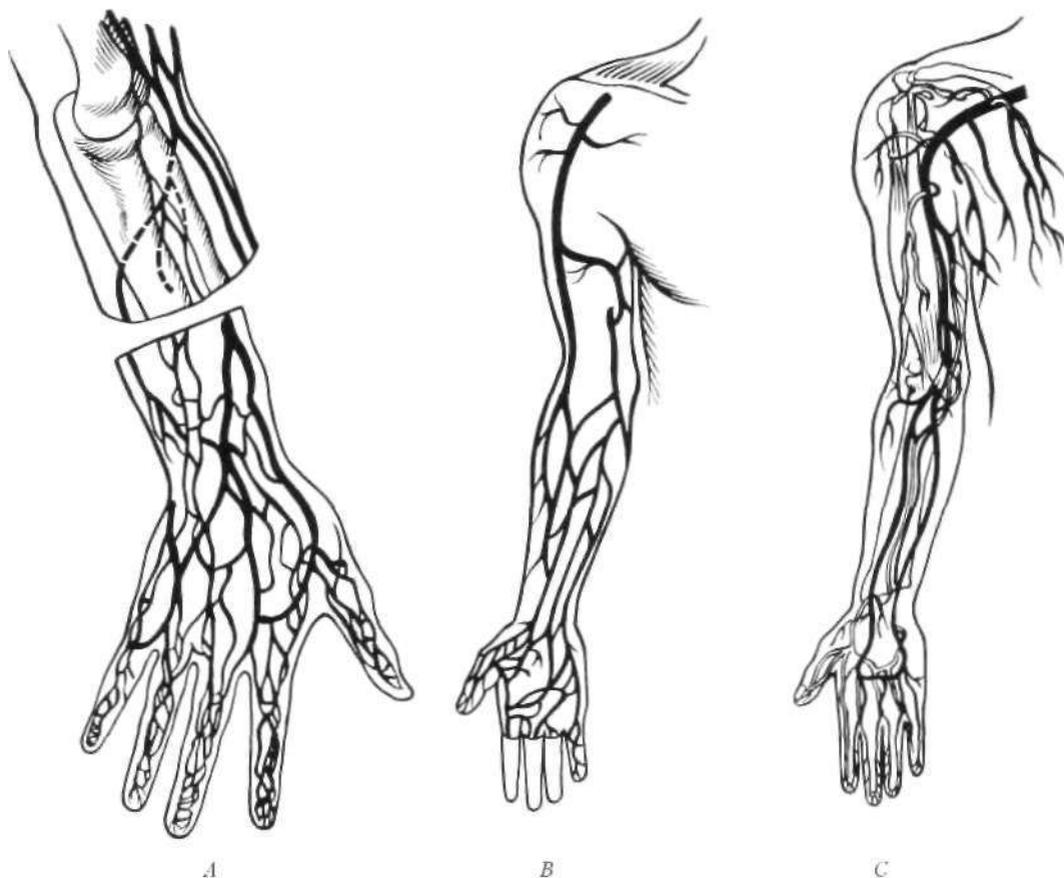


Fig. 10. Blood supply to the upper extremity. A, above, medial view of the elbow. A, bottom, dorsal veins of the hand. B, superficial veins of the arm. C, arteries of the arm.

Table 5
HAND MUSCLE DYNAMICS

Action	Muscles	Total Fick Force ^a (lb.)	Measured Force (lb.)
Hand-on-wrist:			
Volar Flexion	FDS, FDP, FCU, FCR, FPL, APL, PL	730 ^b	50.0 ^c
Dorsal Flexion	EDC, ECU, ECRL, ECRB, EIP, EPL	367	30.0 ^c
Radial Flexion	ECRL, APL, EIP, EPL, ECRB, FCR	244	38.0 ^c
Ulnar Flexion	FCU, ECU	227	29.5 ^c
Prehension:			
Palmar	FDS, FPL, FDP, L, FPB, OP		21.5
Tip	FDS, FPL, FDP, L, FPB, OP		21.0
Lateral	FPB, OP, FPL, I		23.0

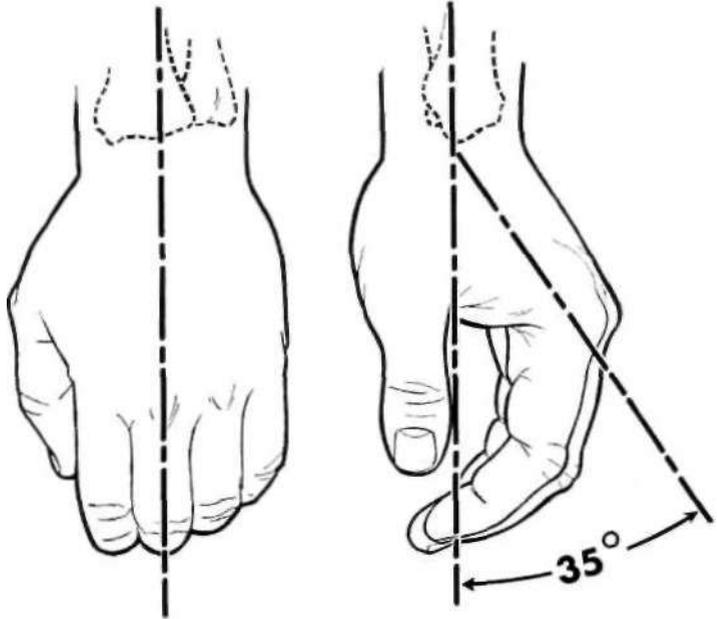
^a From Fick (7).

^b The palmaris longus, absent in about 15 percent of cases, is omitted from the summed Fick forces of volar flexion.

^cAverages from measurements of maximum forces normal to the hand, applied at the metacarpophalangeal joint, on 15 young males at the University of California at Los Angeles (unpublished data).

Fig. 11. The resting hand pattern.

common objects used in everyday life, three types were selected from among those originally classified by Schlesinger (10). These, appearing in Figure 13, are palmar, tip, and lateral prehension, respectively. The frequency with which each of these types occurred in the investigation cited is given in Table 6. While the relative percentages differ in the two types of action, the order of frequency with which the prehension patterns occurred is the same.³



MECHANICAL-ANATOMICAL BASIS or PREHENSION PATTERNS

It is convenient to analyze digital mechanics in terms of flexion-extension variations in the digits, thumb postures, and variations in the radioulnar axis.

INDIVIDUATION OF DIGITAL FLEXION-EXTENSION

Insertion of flexor and extensor muscle systems into several major segments along the proximal-distal axis provides a variety of flexion-extension patterns in the digits. In Figure 7, the essential components are shown schematically for digits I and III. With these attachments, fixation of carpal and metacarpal segments by cocontraction of flexor and extensor carpi muscles provides a firm base for independent movements and fixations of the phalangeal segments. Individual flexions of the second and terminal phalanges stem from separate flexor muscle groups. Such flexor groups, inserted distally, can also cause complete cylindrical-grasp prehension by "rolling

up" the hand (Fig. 13). The counterbalancing digital extensor inserts into the two most distal phalanges and, on contraction, rigidly extends the entire finger. Coordinated action between extensor and flexor groups, however, permits fixed intermediate positions of each segment of the system.

Two common postures of this system may be pictured. In palmar prehension (Fig. 13), the carpal and metacarpal segments commonly fix the wrist in moderate extension, while the digital configuration, mostly metacarpophalangeal flexion coupled with only slight phalangeal flexion, indicates action of the long flexors, strongly modified by the lumbricals and interossei, which are in position not only to contribute to the metacarpophalangeal flexion but also to maintain the phalangeal

Table 6
FREQUENCY OF PREHENSION PATTERNS

Series	Occurrence of Prehension Type		
	Palmar (%)	Tip (%)	Lateral (%)
Pick up	50	17	33
Hold for use	88	2	10

³ Predominance of palmar prehension in both activities accounts for adoption of this pattern in the design of modern artificial hands (page 86).

extension. In tip prehension, the action of muscles upon carpal and metacarpal bones is similar, but distributed flexion in all phalangeal segments indicates predominant flexor activity.

THUMB VERSATILITY PATTERNS

The versatility of the thumb lies, first, in the variety of its flexion-extension patterns and, second, in the adjustable, rotatory plane in which flexion-extension can take place. The first of these is directly analogous to the digital system for the other four fingers, in that for any given metacarpal position there are numerous possible positions of the phalanges. The second effect is due to the relative mobility of the carpometacarpal joint, which

allows the thumb to act in any plane necessary to oppose the digits. The principal oppositions are semidirect, as seen in palmar, tip, and spherical prehensions. Actually, in these cases the plane of the thumb action is inclined 45 to 60 deg. to the palmar plane. In lateral prehension, the plane is approximately parallel to the palmar plane.

VARIATIONS IN THE RADIOULNAR AXIS OF THE HAND

A third principal mode of variation concerns cross-hand alignments. Thus the metacarpophalangeal joints may be drawn into line, and with abducted thumb a flat-hand position is assumed. At the other extreme, the hand is

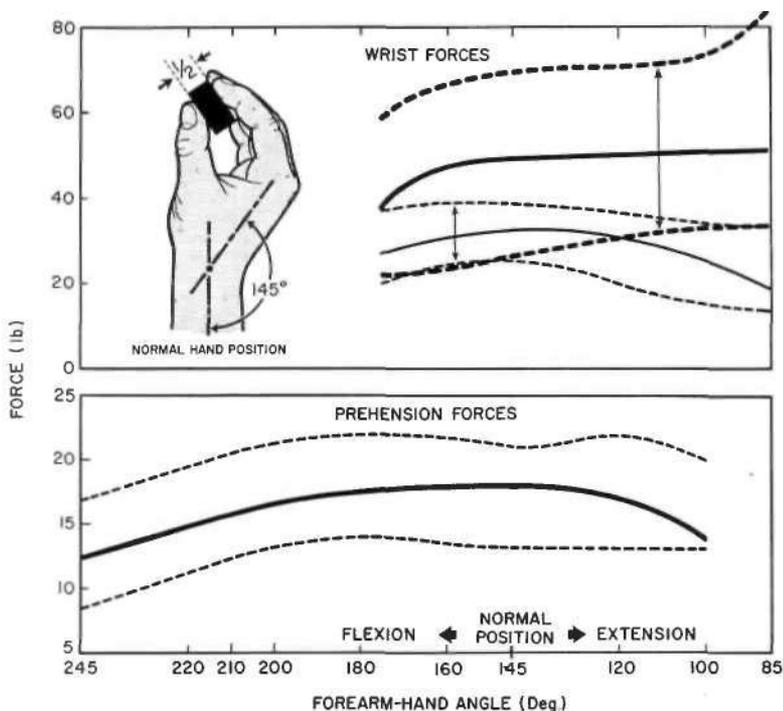


Fig. 12. Effect of forearm-hand angle upon wrist flexion and extension forces and upon prehension forces. Above, relationship between forearm-hand angle and maximum forces of wrist flexion and extension measured at the carpometacarpal joint. Heavy lines, flexion (volar flexion); light lines, extension (dorsal flexion). Solid lines, averages; dotted lines, standard deviations. Unpublished data, UCLA, 15 male subjects. Below, relationship between forearm-hand angle and maximum prehension force measured between thumb and opposing index and middle fingers grasping a 1/2-inch block. Right hand, eight normal male subjects. Solid line, average; dotted lines, standard deviations. From a UC report (14).

cupped for spherical prehension (Fig. 13) as the opponens muscles of thumb and little finger, aided by other adductors and flexors, act to pull these digits toward each other. Similar alignment occurs when a fist is made.

HAND MOVEMENTS

The large number of muscles and joints of the hand obviously provides the equipment for numerous and varied patterns of movement. Not so evident, but equally important in determining complexity and dexterity of motion, are the large areas of the cerebral cortex given over to the coordination of motion and sensation in the hand. Thus, in the motor cortex the area devoted to the hands approximately

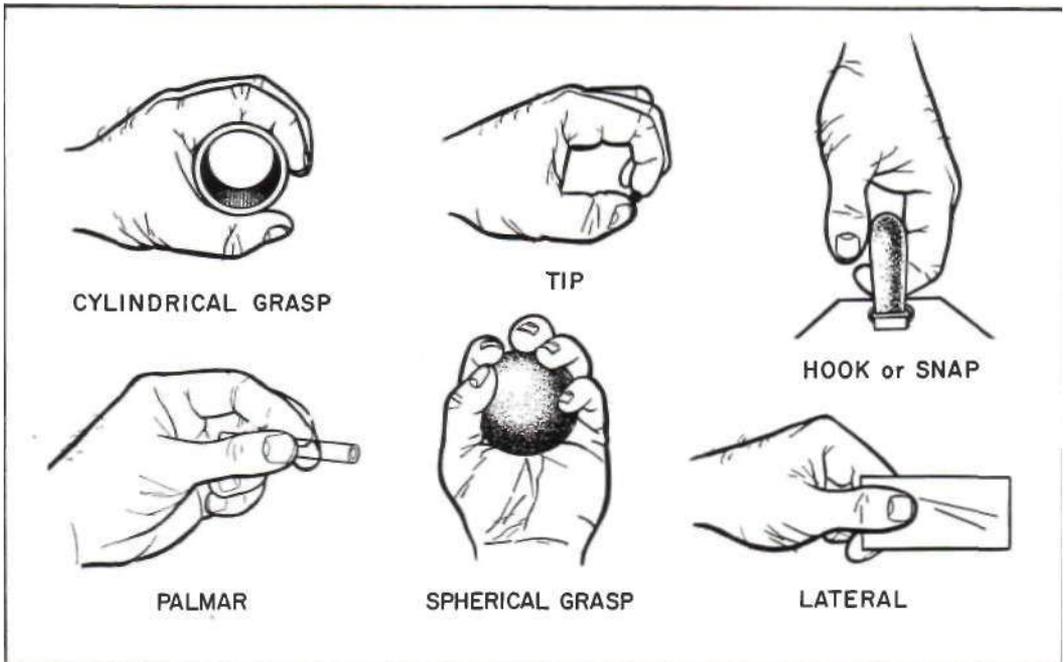


Fig. 13. Six basic types of prehension, as defined by Schlesinger (10).

equals the total area devoted to arms, trunk, and legs (3). This circumstance ensures great potentiality for coordinated movement and for learning new activities. Similarly, the sensory areas are large, so that they determine such advanced functions as stereognosis, the ability to recognize the shape of an object simply by holding it in the hand. The great tactile sensitivity of the hand is, of course, in large part due to the rich supply of sense organs in the hand surface itself. The threshold for touch in the finger tip, for example, is 2 gm. per sq. mm., as compared to 33 and 26 for the forearm and abdomen respectively (2).

The three major types of movement described by Stetson and McDill (11) are in part represented in the hand. They include fixation movements including cocontractions; movements ranging from slow to rapid with control of direction, intensity, and rate; and ballistic movements.

FIXATION MOVEMENTS

In all of the types of prehension described, the hand assumes a fixed position. If the pre-

hended object is unyielding, reactions to the flexion forces are afforded by the object. If the object is fragile, or the hand empty, the hand is maintained in any required prehensile posture by cocontractions of the opposing muscle groups.⁴

The characteristics of balanced muscular action when supporting in the hand loads which produce moments at the wrist have been studied electromyographically by Dempster and Finerty (6). In general, when average potential amplitudes are used to characterize the electrical activity of the muscle, the curves of load-action potential are linear. Frequencies range from 35 to 65 per sec. but bear no clear-cut relationship to load. Typically, each of the muscles traversing the wrist was found to function as agonist, lateral stabilizer, or antagonist as the moment load was shifted from direct opposition at

⁴ There are many other examples of fixation stales, such as the open-claw conformation of the fingers and the extended and rigid index finger for dialing a telephone.

zero deg. to the 90-deg. and then to the 180-deg. positions. The magnitude of the action potentials associated with each of these roles is approximately in the order 4:2:1.

SLOW AND RAPID MOVEMENTS

In movements ranging from slow to rapid, with control of direction, intensity, and rate, there is always some degree of cocontraction to ensure control and to permit changes in force and velocity. A net force in the muscles causes motion. In this category is a long list of activities, such as writing, sewing, tying knots, and pressing the keys of musical instruments. Included are most actions involving differential or integrated motions of the digits.

It is of interest to note that the full capacity for these motions is seldom developed by the average individual. With intensive practice, significant increases in the facility of manipulation, even with simple operations, may be achieved, although individuals differ markedly in the amount of training gain. The average individual has latent potential for development of skill, as shown by the feats of manipulation occasionally evidenced. Knot-tying, cigarette-rolling, and similar complex manipulations may be performed with one hand, as often demonstrated by accomplished unilateral arm amputees. According to Tiffin (13), dexterity differences are correlated neither with mental ability nor with hand shape or dimensions, but Cox (5) points out that they have an important effect on the performance of industrial assembly operations.

BALLISTIC MOVEMENTS

Ballistic movements are rapid motions, usually repetitive, in which active muscular contractions begin the movement, giving momentum to the member, but cease or diminish their activity throughout the latter part of the motion. It is unlikely that, of themselves, the fingers utilize this type of motion to any marked degree. Barnes (7) reviews evidence that in repetitive work finger motions are more fatiguing, less accurate, and slower than are motions of the forearm. Consequently, in repetitive finger activities in which there is a ballistic element, such as piano-playing, typing, and operating a telegraph key, wrist and elbow

motions predominate while the fingers merely position themselves to strike the proper key.

HAND DYNAMICS

The hand muscles, their actions, and contractile forces are given in Table 5 taken from Fick (7). The total Fick force equals the summated forces of the individual muscles participating in the action. For each muscle the force is equal to the physiological cross section (*i.e.*, the total cross section of the muscle taken normal to its fibers) multiplied by the force factor of 10 kg. per sq. cm., estimated by Fick to hold for human muscle. These forces are produced along the axis of the muscle and its tendon, but since the effective moment arm upon any of the wrist or hand joints is small, the *measured* isometric forces are only about 10 percent of the total force.

Among the wrist actions, total forces and measured isometric forces assume the same rank order. The variation, with wrist angle, of both flexor-extensor forces in the wrist and of prehensile forces in the hand is of practical importance as well as theoretical interest. The prehensile force reaches a maximum at a wrist angle of about 145 deg. (Fig. 12, bottom). This is approximately the angle at which the maximum forces of wrist flexion and extension occur (Fig. 12, top). It is common experience that the wrist assumes this angle when very strong prehension is required. The lessened forces at wrist angles toward the extreme positions of flexion or extension are attributable to the well-known force reductions in the isometric length-tension curve as a muscle is markedly stretched or slackened (8). The exception to this rule, seen in the augmented force of flexion at wrist angle 85 deg., apparently means that this degree of wrist extension does not stretch the flexor muscles beyond their force maximum.

CONCLUSION

This, briefly, constitutes the anatomical basis of hand mechanics, from which it can be seen that normal hand function is the result not only of a highly complex and versatile structural arrangement but also of an equally elaborate and fully automatic system of con-

trols. As will be seen later (page 78), such considerations lay down the principal requirements and limiting factors in the design of reasonably successful hand substitutes. When, in the normal hand, any functional feature, either mechanical or sensory-motor, is impaired, manipulative characteristics are reduced correspondingly. In the arm amputee, hand structural elements have been wholly lost, and the most delicate neuromuscular features, those in the hand itself, have been destroyed. Although the lost bone and joint mechanism can be simulated, adequate replacement of the control system defies present ingenuity. Lacking control comparable to that in the natural hand, present-day artificial hands are necessarily limited in the mechanical details that can be utilized, which accounts for the fact that the regain in function currently possible in hand prostheses falls far short of duplicating the natural mechanism.

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LITERATURE CITED

1. Barnes, R. M., *Motion and time study*, Wiley, New York, 1937.
2. Best, C. H., and N. B. Taylor, *Physiological basis of medical practice*, Williams and Wilkins, Baltimore, 1937. p. 1256.
3. Best and Taylor, *op. cit.*, p. 1418.
4. Bunnell, Sterling, *Surgery of the hand*, Lippincott, Philadelphia, 1944.
5. Cox, J. W., *Manual skill*, Cambridge University Press, 1934.
6. Dempster, W. T., and J. C. Finerty, *Relative activity of wrist moving muscles in static support of the wrist joint; an electromyographic study*, *Am. J. Physiol.*, 150:596 (1947).
7. Fick, Rudolf, *Handbuch der Anatomie und Mechanik der Gelenke*, Dritter Teil, G. Fischer, Jena, 1911.
8. Inman, Verne T., and H. J. Ralston, *The mechanics of voluntary muscle*, Chapter 11 in Klopsteg and Wilson's *Human limbs and their substitutes*, McGraw-Hill, New York, 1954.
9. Keller, A. D., C. L. Taylor, and V. Zahm, *Studies to determine the functional requirements for hand and arm prosthesis*, Department of Engineering, University of California at Los Angeles, 1947.
10. Schlesinger, G., *Der mechanische Aufbau der kunstlichen Glieder in Ersatzglieder und Arbeitshilfen*, Springer, Berlin, 1919.
11. Stetson, R. H., and J. A. McDill, *Mechanism of different types of movement*, *Psych. Mono.*, 32(3): 18 (1923).
12. Taylor, Craig L., *The biomechanics of the normal and of the amputated upper extremity*, Chapter 7 in Klopsteg and Wilson's *Human limbs and their substitutes*, McGraw-Hill, New York, 1954.
13. Tiffin, Joseph, *Industrial psychology*, Prentice-Hall, New York, 1947.
14. University of California (Berkeley), Prosthetic Devices Research Project, Subcontractor's Final Report to the Committee on Artificial Limbs, National Research Council, *Fundamental studies of human locomotion and other information relating to design of artificial limbs*, 1947. Vol. II.