May 1955

Artificial Limbs

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National Academy of Sciences

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CONTENTS

ENGINEERING—HOPE OF THE HANDLESS
Eugene F. Murphy 1

THE ANTHROPOLOGY AND SOCIAL SIGNIFICANCE OF THE HUMAN HAND
Ethel J. Alpenfels 4

THE ANATOMY AND MECHANICS OF THE HUMAN HAND
Craig L. Taylor and Robert J. Schwarz 22

SOME PROBLEMS IN THE MANAGEMENT OF UPPER-EXTREMITY AMPUTEES
Frederick E. Vultee 36

THE NOTICEABILITY OF THE COSMETIC GLOVE
Tamara Dembo and Esther Tane-Baskin 47

COLOR REALISM IN THE COSMETIC GLOVE
W. A. Carnelli, M. G. DeFries, and Fred Leonard . 57

THE CHOICE OF TERMINAL DEVICES
Sidney Fishman and Norman Berger 66

THE PRINCIPLES OF ARTIFICIAL-HAND DESIGN
Maurice J. Fletcher and Fred Leonard 78

DIGEST OF MAJOR ACTIVITIES OF THE ARTIFICIAL LIMB PROGRAM 95

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Engineering — Hope of the Handless

EUGENE F. MURPHY, Ph.D.[1]

THE human hand, with its elaborate control system centered in the brain, is doubtless the most widely versatile machine that has ever existed anywhere. Its notorious deficiency lies in its persistent inability to create a similar machine as versatile as itself. This circumstance accounts for the fact that, while there has been from earliest times a great need for hand replacements, all attempts to produce successful hand substitutes have thus far ended in only a rather crude imitation of a very few of the many attributes of the living counterpart. For want of complete knowledge of the natural hand-brain complex, and of the ingenuity requisite even to the most modest simulation of the normal hand, artificial hands have always resembled the natural model in a superficial way only. Voltaire is said to have remarked that Newton, with all his science, did not know how his own hand functioned.

But the science of Newton, basic as it was, is itself remote from the advanced technology of our own day. Failure in hand prosthetics, though owing in part to the difficulty of replacing any living organ with an inanimate contrivance, stems also in part from failure to apply intensively the principles of modern science generally, and of engineering in particular, to the problems of artificial-hand design. Because in general the engineering profession had not theretofore been much concerned with the development of improved artificial limbs, the hand prostheses available a decade ago represented no appreciable improvement over those to be had at the end of World War I.

In all fields of human endeavor, the problems for which men have found tentative solutions in the past often merit the attention of the engineer of today. A new look by competent technologists usually yields gratifying results, for the solutions found by our forebears, while seemingly adequate at the time, do not reflect the progress made in the development of methods of experimental analysis, in the measurement of behavioral characteristics, in the establishment of criteria, in the development of materials, and in the evolution of forming techniques for application of the materials to the needs of man. Just so in the

[1] Chief, Research and Development Division, Prosthetic and Sensory Aids Service (Central Office) Veterans Administration, 252 Seventh Avenue, New York City; member, Technical Committee on Prosthetics, ACAL, NRC.

field of prosthetics, where the problem of matching a device to the human system is particularly acute and where, consequently, the application of new methods holds special promise.

Perhaps the most compelling reason today for the importance of engineering in prosthetics research lies in the approach and methodology now implicit in the profession. Introduction of the requirements of man in a quantitative manner without neglect of the qualitative, subjective aspects places design on a rational basis for the first time in history. During World War II there arose the problem of designing numerous complicated systems to be operable within the limits of human capabilities. In that urgent work, a substantial number of engineers had occasion to become acquainted with certain important physiological and psychological characteristics of man, so that by the end of the war the stage was set for the impact of the engineering profession on the development of prosthetic devices, which is, after all, a unique and particularly challenging field of biomechanics.

When, therefore, in 1945, the then Committee on Prosthetic Devices undertook to conduct basic studies toward the provision of better hand substitutes, it enlisted the services of engineers to cooperate with the medical profession and others in developing the necessary data and in applying the results to improved hand design. In the Artificial Limb Program, principal responsibility for the development of improved hand substitutes has almost from the beginning resided with the Department of Engineering at the University of California, Los Angeles Campus, and with the Army Prosthetics Research Laboratory, Walter Reed Army Medical Center. Out of this cooperative effort have now come not only new and improved devices but also, and perhaps more important, a set of criteria which lay down the basic principles of hand design toward further improvements in the future.

Because of the importance of the hand in all human activities, because of the critical nature of adequate hand replacement in the rehabilitation of upper-extremity amputees, and also because of the rather striking advances that have been made in the design of artificial hands in recent years, this issue of ARTIFICIAL LIMBS is devoted entirely to a little symposium on the hand and its substitutes. The mutual cooperation of the several contributors toward a unified approach to the whole subject is typical of the cooperation that has characterized the Artificial Limb Program since its inception.

The work in prosthetics will, it is to be hoped, serve as a pattern for further investigations jointly by the medical and engineering professions wherever developments in materials, controls, and systems in general can be brought to bear to augment human functions which an individual can himself no longer provide. One continuing problem is that of convincing able young people now studying engineering that a satisfying future exists for them in such cooperative ventures with the medical profession designed to rehabilitate the less fortunate throughout the world. Those now engaged in prosthetics development can be

of great help in presenting to these young men and women the perspective of the future in such a manner that fresh engineering graduates might elect to carry forward the work now already so well under way.

Finally, it ought to be noted that, despite the distinct accomplishments evident at this, the tenth anniversary of the establishment of the Artificial Limb Program, only the first faltering steps have been taken toward the "ideal" prosthetic hand. Structural elements and prehensile function are not enough. It remains to provide some reasonable substitute for the sensory-motor apparatus which, in the living hand, is of such consummate perfection as to beggar description. A problem like this should charge the imagination of any young engineer in search of a field of application for service. To him belongs the future in prosthetics research.

The Anthropology and Social Significance of the Human Hand

ETHEL J. ALPENFELS, D.Sc.[1]

A DEFINITIVE study of the anthropology of the human hand has yet to be written. Certain investigators, notably Krogman *{17),* Schultz *(28,29),* Ashley-Montagu *(2),* Clark (5), and Huxley *(13),* have done intensive work on specific aspects of the morphology of the human hand. Nevertheless, the paucity of published studies, the fragmentary nature of the research, and the failure to attempt any but the most general conclusions make it difficult to summarize in a short article the present status of the hand in human evolution. Authorities differ both in opinion and in practice as to the value of anthropometric measurements in tracing the lines along which specialization has moved in the evolution of the hand. Published materials on the social significance of the hand are, however, numerous, and the importance of the hand as an organ both of performance and of perception has been recognized in all fields of the social sciences.

Man alone has a hand. He uses it as a tool, as a symbol, and as a weapon. A whole literature of legend, folklore, superstition, and myth has been built up around the human hand. As an organ of performance it serves as eyes for the blind, the mute talk with it, and it has become a symbol of salutation, supplication, and condemnation. The hand has played a part in the creative life of every known society, and it has come to be symbolic or representative of the *whole* person in art, in drama, and in the dance. Students of constitutional types have used the hand as a means of classification, and the correlation between mental ability and manual dexterity has been the subject of much research. At the University of Pennsylvania, Krogman, using x-rays of the hand, currently is demonstrating new and important aspects of the interrelation of a child's growth and mental age. Thus the hand, perhaps because it is also dominant in the world of action, has come to be interpreted and understood best in its social aspects.

But in a sense the human hand is a paradox. Although it is said to be the highest achievement of primate evolution, research to date shows it to be no more than a variation of a primitive vertebrate plan. The successive stages of evolution give proof, if proof be needed, that our sensitive and mobile hands, with their opposable thumbs, are part of man's vertebrate ancestry.

In the suborder Lemuroidea, both recent and extinct, are found pawlike hands. The fourth digit[2] is elongated and, together with the first digit, acts like a pair of pincers to grasp a bough. Hooten *(12)* has pointed out that this is an adaptation found in all the

[1] Professor of Anthropology, New York University, New York City.

[2] Meaning that digit corresponding to the "ring finger" in man. Among anatomists generally, at least two systems for identifying hand digits are in accepted scientific usage, often interchangeably by the same writer. A common convention is to number the digits from I to V, beginning with the thumb as digit I and ending with the little finger as digit V (Fig. 1). But many competent writers, thinking of the hand as having a "thumb" and four "fingers," label the "fingers" as first, second, third, and fourth, meaning the index finger, the middle finger, the ring finger, and the little finger or pinkie, respectively. Throughout this issue of ARTIFICIAL LIMBS, it is considered that the normal hand has five digits, one of which is a "thumb," the other four being "fingers." A "digit" is here referred to with the understanding that digit I is the thumb "Fingers" are referred to as being numbered beginning with the index finger as the first finger.—ED.

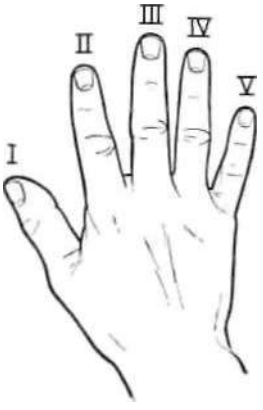

Fig. 1. One conventional method of identifying the digits of the hand. Some authorities prefer to think of the hand as possessing a thumb and four fingers. Both methods of nomenclature occur throughout this issue of ARTIFICIAL LIMBS.

lemurs, enabling them to maintain a more secure hold on boughs of large diameter. In lemurs, all of the digits are flat-nailed (except in the aye-aye, which has kept a number of primitive anatomical features), and several modifications appear in the carpal pattern.

In the suborder Tarsioidea, entirely arboreal, specialization of the hind limbs for hopping frees the hands not only for grasping but for feeding as well. The hind limb is longer than the forelimb, all of the terminal phalanges are flat-nailed, and the terminal digital pads have curious discs, almost like suction cups, enabling the tarsier to support himself on a smooth surface.

These and other adaptations foreshadow higher primate development (Fig. 2), but we must look further to find man's place in the primate scheme. The suborder Anthropoidea, the third and highest of the primate group, includes larger arboreal forms. Longer forelimbs, together with a relatively shorter thumb (approaching atrophy in some forms), provide a means of brachiation. It has been suggested that the short thumb is related to the specialization of the hand as a grasping mechanism, permitting a quick release of the hand in swinging from one branch to another. But in this suborder the hands still retain their primitive features, and only in certain of the Old World Monkeys do the proportions of the digits approach those of man. The emancipated hands of the anthropoids, with thumbs that rotate and oppose the other finger tips, are directed by a more complex nervous system and a larger and better-developed brain. Liberation of the hand may have been one of the decisive forces in the descent of certain anthropoids to the ground.

THE EVOLUTION OF THE HAND

LINKS WITH THE PAST

Man's hand retains the ancient pentadactyl pattern found in early vertebrates. Geological records show that, during the Devonian period of Silurian times, primitive sharks appeared having typical paired fins corresponding to the paired limbs in man, and these organs were destined to give rise to later and higher forms. But there is a great difference belween the paired limbs of the early forerunners of present-day fishes and the pentadactyl limbs of other vertebrates. All of the steps are not yet clear, and the gap between the ancient fishes and the amphibians has not yet been bridged, but it appears that in the early amphibians the migration from water to land led to adaptations and modifications, especially in the area of the shoulder and pelvic girdles.

These early ancestors of the primates had short legs, which grew progressively longer in the mammalian stage *(26),* and they walked flat-footed. The ability of the limbs to rotate brought about changes in the entire body. Striking homologies can be found in the hand and arm of man, the wing of a bat, and the foreleg of the frog. Where there are fewer digits, as in the hoof of the horse or the wing of the bird, the reduction has been due to adaptation to special environmental conditions *(5,13, 26).* Such reductions make for greater speed in the specialized limbs of the horse.

UPRIGHT POSTURE AND DIFFERENTIATION

The release of the hand from the requirements of locomotion, accompanied by the specialization of the foot and hind limbs for that purpose, led to upright posture (Fig. 3). Evidences of divergent evolutionary trends in the primate order are clearly distinguishable in the primate hand, especially those relating to limb length and trunk length (Fig. 4). Only the mountain gorilla has a hand shorter than that of man, not only with respect to limb length but in relation to trunk length. The longest hands among the great apes are those of the gibbon, the orangutan, and the chimpanzee. Specialists in the evolution of the hand

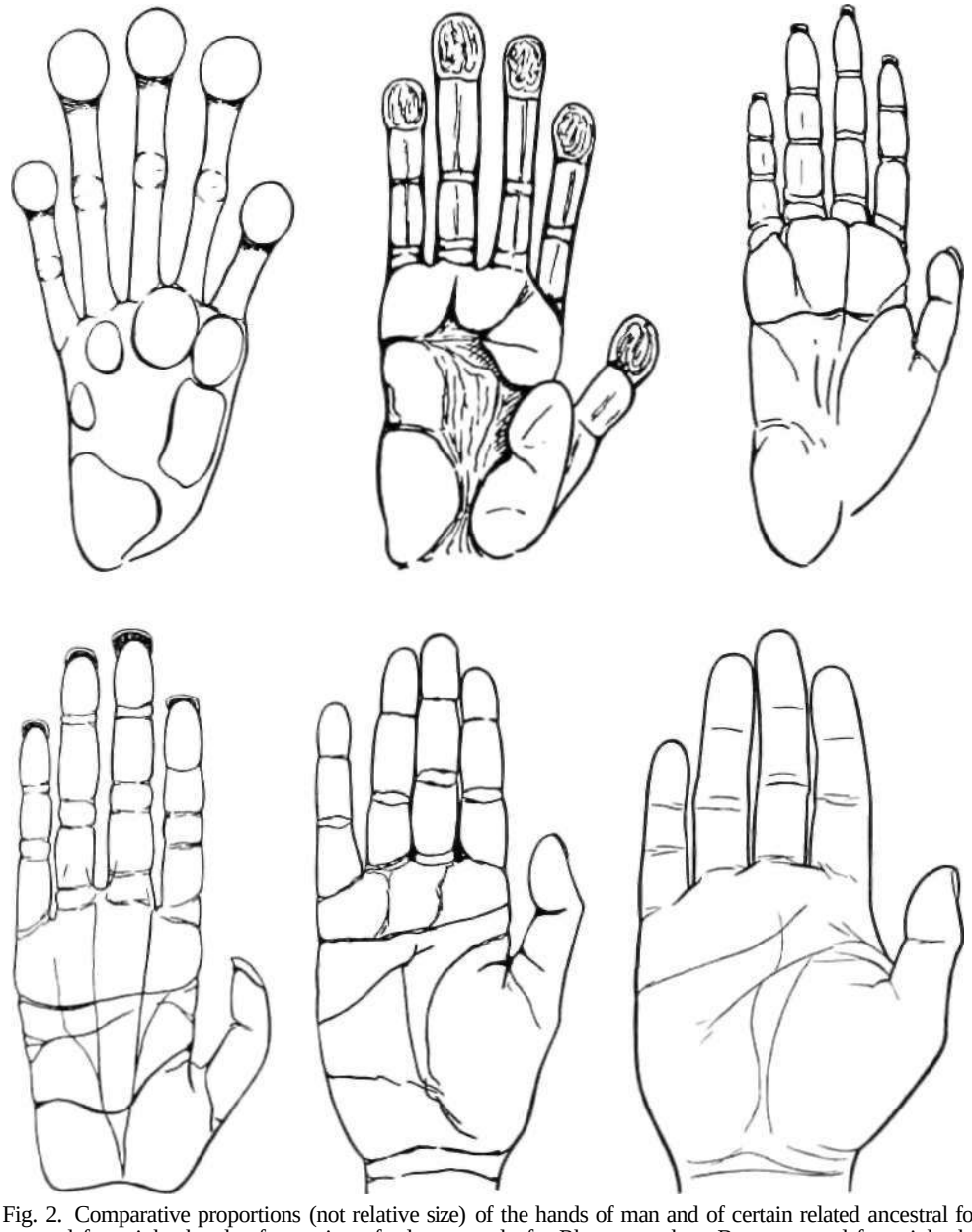

Fig. 2. Comparative proportions (not relative size) of the hands of man and of certain related ancestral forms. Top row, left to right, hands of a tarsier, of a lemur, and of a Rhesus monkey. Bottom row, left to right, hands of a chimpanzee, of a human with atypical simian characteristics, and of normal man. In all cases except that of the lemur, the digital formula i s 3 > 4 > 2 > 5 > 1. From Jones *(14),* by permission of Bailliere, Tindall, and Cox, Ltd.

have attributed the long, slender hands of these genera to brachiation and suspension, behavior that elongates not only the arms but the hands as well, especially the fingers and the metacarpal bones.

As for the length of the thumb, man and the other great apes show sharp divergence, especially when the thumb is considered with respect to hand length. As contrasted with the short thumb of the anthropoid apes, man's

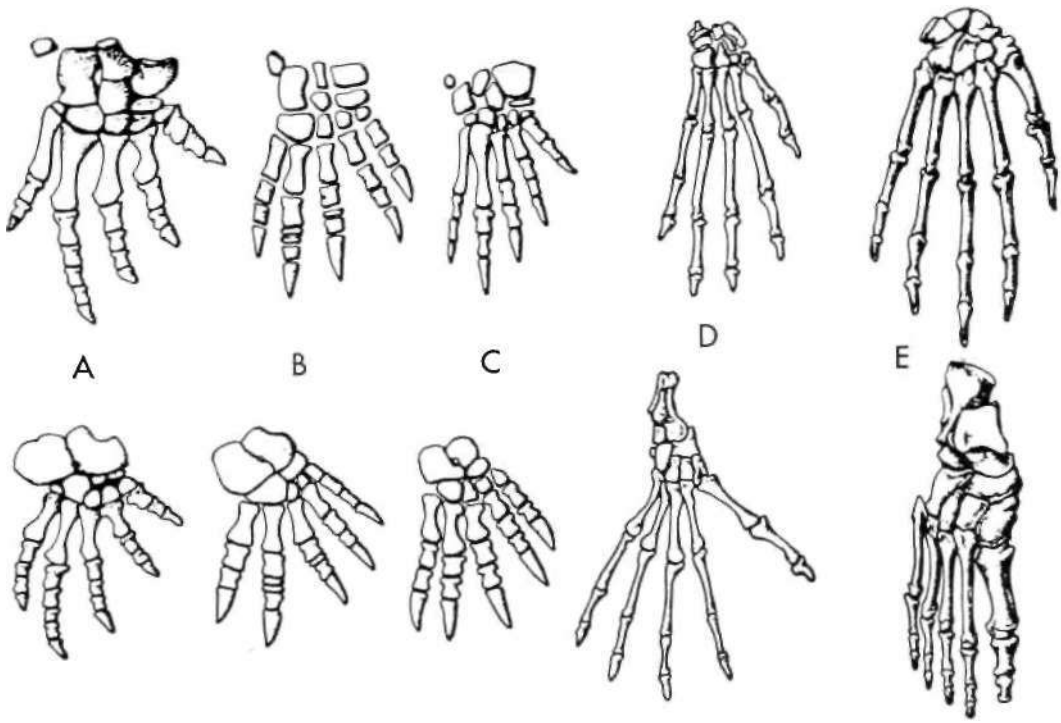

Fig. 3. The evolution of the hand (top row) and foot (bottom row), as revealed in skeletal structure. *A,* a primitive reptile; *B, C,* mammal-like reptiles; *D,* a lemur, representing a primitive mammalian type; *E,* man. Note the reduction in the number of joints in the toes, the specialization of the proximal ankle bones in mammals, some reduction in the number of wrist and ankle bones, and the variations in the thumb and great toe From Romer *(25),* by permission of The University of Chicago Press

thumb is long and well developed. Attempts to explain this difference have led to an either-or position. Either the thumbs of the apes have atrophied as a result of their arboreal life or man's thumbs have lengthened in the evolutionary process.

THE SHOULDER AND UPPER ARM

In man the shoulder and upper arm are adapted for strength. As for the other portions of the arm down to and including the hand, the more distal the part the more it is adapted for complex and delicate functions and the less for strength. The pectoral girdle in man consists of three bones. The scapula is directed dorsally, the coracoid process extends forward and downward to meet the sternum, and, anterior to the coracoid, the clavicle connects scapula and sternum. Because the pectoral girdle is not joined directly to the spine, though it may articulate with the sternum, the structure permits great freedom of motion in the shoulder area. Briefly, the human arm, supported and controled by a large number of muscles, together with the elbow and wrist joints, gives freedom to a hand that has become the willing servant of the human intellect.

MAN'S OPPOSABLE THUMB

The powerful and well-developed thumb of man is one of his few uniquely human characteristics. Through successive stages of vertebrate evolution, the thumb has separated from the other fingers and developed specialized musculature. In the Anthropoidea, the feature of opposability led to greater tactile and exploratory facility. Man's thumb, comparatively twice as long as that of some of the anthropoids, reveals a steady increase in absolute and relative length (Figs. 2 and 4) and, at the same time, the steady development of

opposability, extensibility, and flexibility. When the "hand" of the ape is compared with the hand of man it becomes, in the words of Krogman *(17),* a "misnomer." In the ape, hands are hands by definition only. Although man's hand, the end-product of our evolutionary development, retains the basic, primitive, pentadactyl pattern common to all land vertebrates, it nevertheless is uniquely human. The earliest animal footprint known (from the Permian of the Tambach in Thuringia) is so similar in appearance to that of the human hand that the animal which left the fossil print was named "Cheirotherium," or the "handbeast" *(2,5,12,17).*

VARIATIONS OF THE HUMAN HAND

The morphological pattern of man's hand shows its affinity to the "hands" of other animals. But while man has kept the primitive pattern, other animals have specialized. In birds, for example, the hand has become a wing, in the horse a hoof, in the whale a flipper, in the dog a paw, and so on. According to Hooton *(12),* Crawford has demonstrated the difference between tool-using, as in man, and tool-growing, as in most animals. Animals use no tools other than those developed out of the materials furnished by their own bodies. Man, however, was *(12)* "the first animal to grow a limb outside himself by making tools out of wood and stone." Furthermore, the limbs of animals are specialized for single purposes only. The horse can run, the mole can dig, but neither can climb; man makes instruments that are imitations of the body tools of other animals—a digging stick, an awl, a scraper, or a dagger *(34).* The power and versatility of the human hand rests, in part, upon its generalized pattern. But it is the human brain, with its intricate and elaborated nervous system, that coordinates man's eye and hand. Thus, man is born with a hand free to do the bidding of his expanded brain.

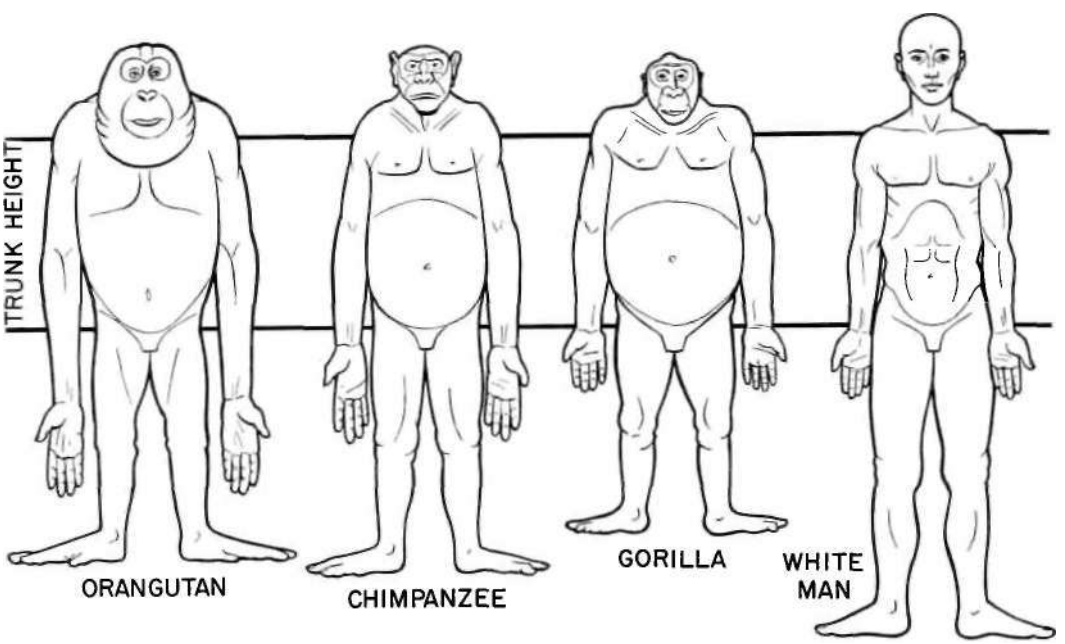

Fig 4. Exact diagrammatic front views of the four largest primates at fully adult age, drawn from detailed measurements on actual specimens, hair omitted, and all reduced to the same trunk height. From Romer *(25),* by permission of The University of Chicago Press. Originally constructed by A. H. Schultz. Note that, from orang to chimp to gorilla to man, both limb length and hand length generally decrease with respect to trunk height. Only the gorilla has a hand shorter than that of man.

THE ANTHROPOMETRY OF THE HAND

EARLY STUDIES

The past fifty years have seen a gradual increase in the literature devoted to the anthropometry of the human body. But until that time, individual investigators had gone their separate ways, and there was little concurrence on standardization of the measurements to be employed, on the way in which these measurements were to be taken, or on the instruments to be used. Furthermore, just as in the osteological studies conducted in anthropological museums, early research on living animals was devoted largely to the head and facial features, and only later was study extended to the remainder of the body. Hence the dearth of anthropometric studies on the hand is easy to understand. Lacking, also, are routine osteometric recordings and systematic measurements and indices that could provide the comparative anatomical data necessary for a definitive work on the evolution of the human hand.

THE LACK OF DATA

Authorities appear to agree that no part of the human body has been as neglected as has the hand *(2,31).* The reasons for this situation are many, but perhaps the most important one is the scarcity of fossilized primate hands, probably owing to the fact that these bones are small, fragile, and easily destroyed by the action of the forces of nature. Nor are the anthropological collections of complete hands of the modern anthropoids anywhere near adequate. During the past few years, individual investigators and museums have been attempting to increase the number of complete hands available for study, but the collections still are quite inadequate. Moreover, as was demonstrated at the University of Chicago, skeletons often turn out to be composites of many separate individuals and, therefore, of little use in anthropometric studies *(10).* These handicaps, together with the complexity and the extreme variations found in the human hand, make it exceedingly difficult to get accurate results.

THE NEW FOCUS

The early work in comparative anthropometry was devoted entirely lo race differentiation *(4).* At the present time, however, that interest is lagging, and extensive growth studies of the epiphyseal closures of the metacarpals and the phalanges are being conducted at the University of Pennsylvania *(11).* The x-ray technique, used for many years, has become the major tool by means of which the anthropometrist and anatomist can study living persons. It is dependable and important, especially in studying the highly differentiated parts of the human hand.

CLASSIFICATION

The morphology of the hand has proved useful in classifying hand types. Wechsler's system *(17)* is based upon four hand dimensions (Fig. 5). From all possible combinations of length and three breadths, he derives six index categories, as shown in Table 1. Thus, the long, narrow hand type in man would be, for example, 1-1-1-2-4-3, that of the short, broad hand 4-4-4-4-4-4.

HANDEDNESS IN MAN

RIGHT AND LEFT—GOOD AND EVIL

The cultural world in which man lives, both in preliterate and in technologically advanced societies, tends to be a "right-handed" world. Cross-cultural studies reveal that different sides of the body, the left or the right, are associated with different social activities. In India, the right side and the right hand perform tasks considered to be "clean," while the left side and the left hand perform tasks considered to be "unclean." The two types of activities are separated rigidly. The right hand, for example, is used for cooking and eating, whereas the left hand is used in bathing, elimination, or activities associated with sex. Indeed, it is common in many areas of the world to find food related to the right hand, while the left hand is associated with sex *(19).*

The right and left hand have come to symbolize good as opposed to evil, gods as opposed to demons. Hence, they are considered as two forces constantly at war with one another. The shadow plays of the Balinese illustrate the widespread association of good and evil with the right and left side respectively. The mystic story teller takes the marionettes out one by

Fig. 5. Hand measurements according to Wechsler. From Krogman (//), by permission of *Ciba Symposia.*

1. *Stylion radiale,* at tip of radial styloid process.
2. *Stylion idnare,* at tip of ulnar styloid process.
3. *Interslylion,* mid-point of line connecting 1 and 2.
4. *Daclylion III,* at tip of third finger.
5. *Metacarpale radiale,* at metacarpophalangeal junction of index finger.
6 *Metacarpale ulnare,* at metacarpophalangeal junction of little finger.
7. *Proxindicion,* at proximal interphalangeal junction of index finger.
8. *Ulnoquintion,* at intersection on ulnar side of little finger of line perpendicular *[sic]* to length dimension, drawn from 7.
9. *Dislindicion,* at distal interphalangeal junction of index finger.
10. *Ulnoquartion,* at intersection on ulnar side of ring finger of line perpendicular *[sic]* to length dimension, drawn from 9.

Table 1

WECHSLER'S HAND INDICES

Length-Breadth Index I (Hand breadth I × 100/Hand length)	
1. Hyperdolichocheir (hdch)	x–40.9
2. Dolichocheir (dch)	41 0–43.9
3. Mesocheir (mch)	44 0–46 9
4. Brachycheir (bch)	47.0–49.9
5. Hyperbrachycheir (hbch)	50 0–x
Length-Breadth Index II (Hand breadth II × 100/Hand length)	
1. Ultralongiman (ulm)	x–32.9
2. Longiman (lm)	33.0–36.9
3. Medioman (mm)	37.0–40.9
4. Breviman (bm)	41.0–44.9
5. Ultrabreviman (ubm)	45.0–x
Length-Breadth Index III (Hand breadth III × 100/Hand length)	
1. Hyperdolichaktin (hda)	x–23.9
2. Dolichaktin (da)	24.0–26.9
3. Mesaktin (ma)	27.0–29.9
4. Brachyaktin (ba)	30 0–32 9
5. Hyperbrachyaktin (hba)	33 0–x
Hand-Breadth Index A (Hand breadth II × 100/Hand breadth I)	
1. Very strongly convergent	x–78.9
2. Strongly convergent	79.0–82.9
3. Mid-convergent	83.0–86.9
4. Weakly convergent	87 0–90 9
5. Very weakly convergent	91.0–94.9
6. Parallel	95.0–x
Hand-Breadth Index B (Hand breadth III × 100/Hand breadth II)	
1. Hektoklin (hkl)	x–65.9
2. Pemptoklin (pekl)	66 0–68.9
3. Tetartoklin (tekl)	69 0–71 9
4. Tritoklin (trkl)	72 0–74 9
5. Deuteroklin (dtkl)	75.0–77 9
6. Protoklin (prkl)	78 0–x
Hand-Breadth Index C (Hand breadth III × 100/Hand breadth I)	
0. Ultrafortistrikt (ufst)	x–49.9
1. Fortistrikt (fst)	50 0–53.9
2. Subfortistrikt (sfst)	54 0–57.9
3. Mediostrikt (mst)	58.0–61.9
4. Sublevistrikt (slst)	62.0–65.9
5. Levistrikt (lst)	66.0–69.0
6. Ultralevistrikt (ulst)	70.0–x

one, placing the "good" and "noble" characters at his right side and, at the left, the "evil" and "sinister" characters. In the end, truth and goodness always win, which demonstrates the triumph of the magical powers of the right side. At all important life crises—birth, death, marriage, initiation ceremonies—this magic balance between left and right is maintained. Among the Tiv of Nigeria, the afterbirth of a boy child is always buried to the left of the door in order to propitiate the evil spirits residing there. In Bali, a boy's placenta is buried

on the right and a girl's on the left side of the entrance to the house *(6)*.

CASTE AND THE HAND

The symbolism of the hands in ceremonial rites has, in various ways, come to indicate social class and caste. Among the Balinese, for example, it is a mark of social distinction to wear long nails, but only the priest may wear them on both hands. The giant-god of pre-Hindu times is believed to have carved out all of the caves with the fingernails of his left hand. The Indian caste system is noted for a unique feature in that many of the castes are divided into two sections called the "right-hand" (Balagai) and the "left-hand" (Yedagai) castes. Certain socially lower artisan castes, such as workers in leather, belong to the left-hand subgroup *(21)*. Among the Motu of Papua, the moieties are grouped by the left and right hand. Members of the right-hand moiety have senior status in matters of inheritance, while members of the left-hand moiety have junior descent status *(27)*.

OTHER INFLUENCES

Music for the piano usually is written in such a way that the melody is carried by the right hand. Threads in bolts, pipes, and even in glass jars are right-handed. Soup and gravy ladles, fish forks, and meat grinders—in fact, the majority of our manufactured products—are designed for the right-handed individual. Can the custom of men buttoning their coats on the right side and women on the left be a survival from our primitive past when the right was reserved for men because it was "good" and the left for women because it was "evil"? Our society is belatedly recognizing the right of sinistrodextral people to full participation in our culture. Banks are issuing left-handed checkbooks, left-handed armchair desks have been introduced in schools, and left-handed scissors and other implements and tools now are available.

HANDEDNESS IN EARLY MAN

Whatever the reasons for associating right with "good" and left with "evil," the fact remains that man is predominantly right-handed, a fact that appears to have been true even in prehistoric times. Early writers explained the enigma of right-handedness in the Lamarckian sense of "use and disuse." They noted that, since the heart was located on the left side of the body, the warrior carried his shield in his left hand. The right hand was free and, through more frequent use, developed in both size and dexterity. This "acquired" characteristic was passed on to succeeding generations.

During the nineteenth century, as the authenticity of plant and animal fossils was established, and with the growth of anthropology as a more exact science, numerous archaeological sites were excavated. By the beginning of the twentieth century, thousands of artifacts had been uncovered, more precise data were available, and the picture of life in prehistoric times began to emerge in greater detail. The oldest implement found in Europe was beveled for grasping between the right thumb and first finger. The implements of primitive Paleolithic sculptors were found to approximate in number and in form those of modern sculptors. All of the tools uncovered in a Spanish cave, said to have been inhabited during Solutrean times, are designed to fit the hand, and, from the almost perfect adaptation of these instruments, we may infer that these ancient artists were right-handed *(22)*. Based upon the frequency of left-handed flint tools found *in situ* in France, other authorities, Krogman *(17)* for example, note that the incidence of left-handedness increased during the New Stone Age.

HANDEDNESS IN APES

During the past three decades, handedness in the apes has been studied extensively in the United States. Yerkes *(35)*, in his classical work on the apes, found that handedness appears in chimpanzees. He points out that they use one hand consistently for certain purposes and the other hand for other activities. He says, however, that right-handed dominance has not been demonstrated and that the three types of motor activity found in man (right- and left-handedness and ambidexterity) occur with about equal frequency.

THE CHICK EMBRYO

The problem of left- and right-handedness in chickens has been reported. At about the 38th hour in the chick embryo, certain processes are initiated that result in what may

be termed very loosely a "right-handed embryo." In certain chemicals, the molecular structure is "left-handed" in that it is of the nature of the mirror image of the "right-handed" counterpart. After a number of hours of incubation, fertile chicken eggs exposed to such "left-handed" chemicals evidence a "left-handed" type of flexure of the developing brain.

ASYMMETRY

Yerkes *(35)* holds with the current opinion that asymmetry of the left and right hand (Fig. 6) is related to a general asymmetry of the entire body. The right and left leg in man, for example, also differ in strength and in dexterity. Similarly, the right lung is slightly heavier, the abdominal viscera are heavier on the right side, both the spine and pelvic regions display asymmetry, and hence the center of gravity of the body is slightly to the right. Kahn *(15)* reports a number of experiments which demonstrate that, owing to this asymmetry, every blind wandering ends in a circle. Thus, man cannot write, nor walk, nor drive a car blindfolded without becoming a victim of his physical asymmetry.

Endocranial casts of the brain cavities of fossil and of modern man support this evidence, and here too asymmetry appears. The left occipital portion of the brain predominates to produce right-handedness, a fact established by Smith *(30).* One school of thought claims that this asymmetry of the brain represents a primitive character in the higher apes and man. According to Clark (5), however, Keith maintains that, on the contrary, asymmetry represents an evolutionary advance.

The general physical asymmetry of the body is associated with a social asymmetry in our human prejudice against the left side. The human preference for right-handed tools and artifacts has, somehow, invaded the social and moral life. There also is a *sinistra* and *dextera* view of the world now fixed in our vocabulary.

HANDEDNESS IN LANGUAGE

We speak of dexterity (from the Latin "dexter," connoting "right," "favorable") in referring to skill, and this idea has been traced back to Sanskrit, the ancient literary language of India. From the category of physical things, the right hand has reached out to influence many other areas of human life. To be "orthodox" is to follow the "right" or "true" opinion. The concept of legal justice comes from the French "droit," meaning "right" or "law." Contrariwise, the word "left" symbolizes "evil," "weak," "awkward." The word for "left" in French is "gauche," meaning "awkward." The Latin "sinister," meaning "left," rarely applies to that which threatens but, rather, to that which is known to act covertly or insidiously. The bar sinister is the heraldic symbol of bastardy. A man who marries below his social rank gives his left hand, not his right, to his bride. Thus, in our own culture today there survive in our language and customs the social implications that historically have characterized handedness in man.

THE HAND AS A SENSORY ORGAN

THE SENSORY EXPERIENCE

Although prehension is the major function of the hand, the hand is, at the same time, one of man's primary sense organs. This tactile quality provides sensory experience that may be grouped into four general categories *(16).* The first consists of "surface sensations"—stimulation generated by touching tangible objects. The second is termed "space-filling"—stimulation generated by pulling the hand through liquid substance. "Spacelike sensations," comprising the third category, relate to the touch of distinctively shaped objects felt through a heavy material. Finally, there are "penetrable-surface sensations," experienced, for example, by a physician as he palpates some part of the body to locate, through the outer layer of flesh, some abnormal condition in deeper tissue.

Movement is indispensable in sensory experience, and experimentation demonstrates that even the "imaginary" touch sensations are located in the finger tips. According to Katz *(16),* it is quite impossible to call up the image of touch without, in imagination, moving the hand. The moment we imagine our hands at rest, the image becomes uncertain or disappears.

When body and ambient temperature are equalized, the hand may be used as an instru-

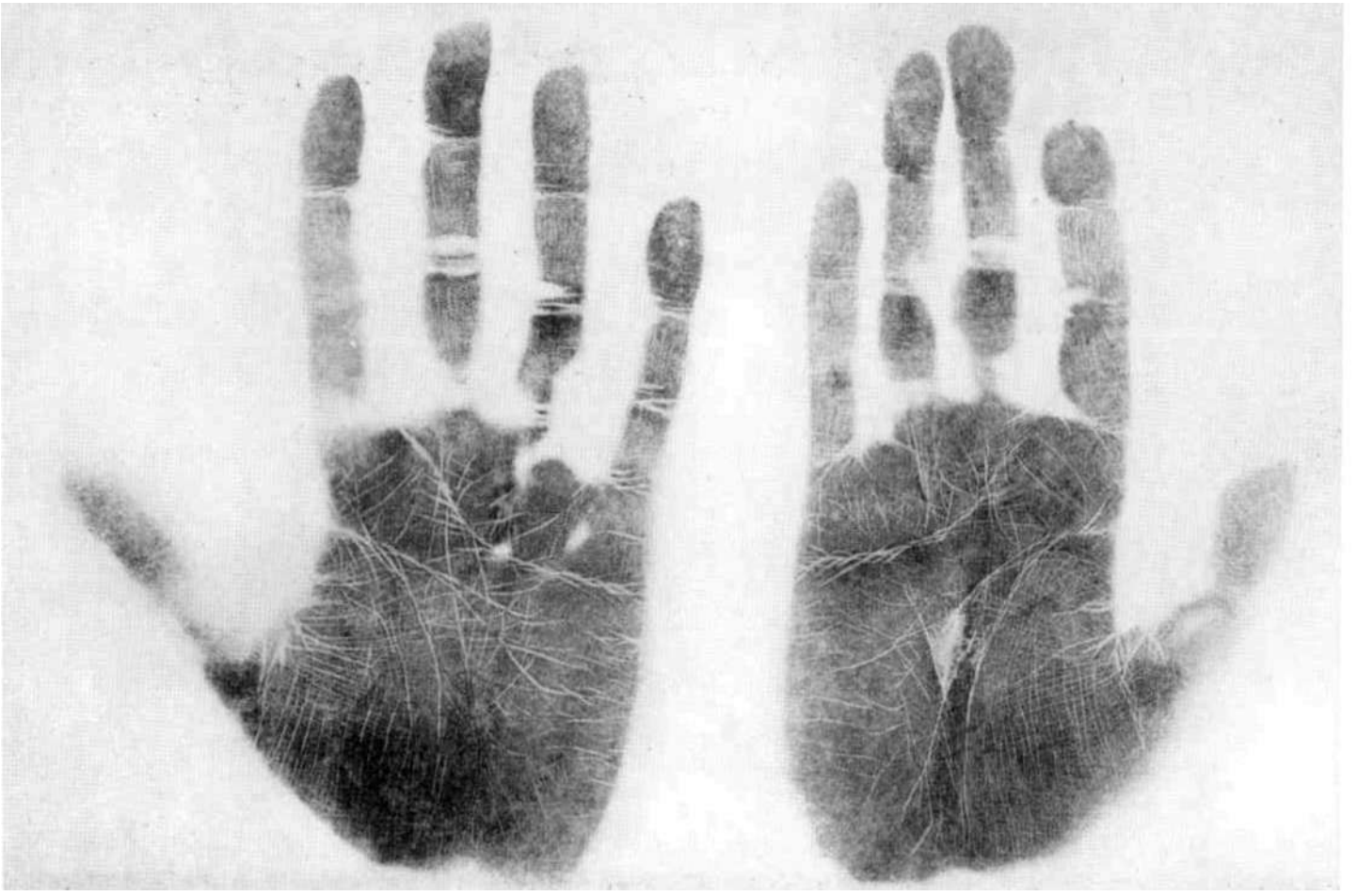

Fig. 6. Typical difference between the right and left hands of a single individual. The right has a shorter palm and longer fingers, and the long longitudinal line is more marked. From Wolff *(33).* by permission of Methucn and Co., Ltd.

ment for the perception of the relative levels of heat and cold. Preliminary determination of body temperature can be determined by placing the hand on the forehead. In folk society, for example, where accurate measures of determining fever temperature are not available, a normal hand placed upon the forehead is used to determine the presence of fever.

A PERCUSSIVE TOOL

The human hand can also be used as a percussion instrument. With an apparatus which he called "the percussion phantom,"[3] von Götzen found that vibratory impulses generated by finger percussion can be felt even when the auditory sense is eliminated.

A VIBRATORY TOOL

Vibratory sensations, as perceived by the hand, are of importance in teaching the deaf to speak. By placing one hand on the larynx of a speaker and the other hand on his own larynx, a deaf-mute learns the vibration patterns of speech sounds. When the patterns "heard" by his left and right hand are identical, the student has succeeded in imitating the sound. Helen Keller utilizes the vibratory phenomena when she "hears" music by placing her hand on the piano.

[3] Katz *(16)* describes the apparatus as a square wooden box, about 60 centimeters long by 8 centimeters deep, and open at the top. Around the top edge a strip of felt is fitted, and over the whole a thick cardboard square is fastened; this side of the box is clamped on with metal clips. The cardboard is strong enough to resist considerable pressure without sagging. On the underside of the cardboard, *i.e.,* inside the box, objects of different shapes—for example, round, elliptical, or heart-shaped objects—are pasted to substantial pieces of lead which appear either as matrices or as patrices, *i.e.,* they are cut into or cut out of lead. The thickness of the plate is chosen according to the degree of difficulty of the percussion task to be presented to the student. In general, the thicker the plate, the easier the task. The plates are so arranged that the figure is located in the middle of ihe underside of the cardboard. Each cardboard is fitted with one figure (if necessary, composed of two parts), so that there are as many cardboards as there are figures required for the test. Students were asked to determine, through percussion alone, the form of figures cut into or out of the lead plates.

THE HUMAN HAND IN ART

Through the ages the human hand has appeared in all of the creative arts of every culture *(1,3,24).* A single line, a schematic portrayal, a simple gesture of the hand, and character and personality stand revealed as clearly as they are seen in the human face. Recently, in the Kefauver investigation of crime in New York City, the television camera focused on the hands of a witness, and millions in the television audience watched while hands expressed feelings that man has taught his face to disguise.

In the creative arts, the hand speaks, and one senses the tremendous power of the hand to convey human emotions. The hands are the organs of the body which, except for the face, have been used most often in the various art forms to express human feeling. The hands point or lead or command; the hands cry out in agony or they lie quietly sleeping; the hands have moods, character, and, in a wider sense, their own particular beauty. From prehistoric times to our own day, in every society known to science, the hands symbolize cultural behaviors, values, and beliefs.

PAINTING AND SCULPTURE

Many studies of the hand appear in the traditions of western art. From schematic and conventional hand portraits, the artists of the fifteenth century began to draw anatomically correct hands, and, slowly but surely, the hand was seen as having a personality and a culture of its own. Albrecht Dürer (1471-1528) devoted a lifetime to the study of anatomy, and in his studies of hands the lines, the curves, the veins, the wrinkles delineate the complexity of the human hand (Fig. 7). In another medium, the French sculptor Auguste Rodin (1840-1917) deliberately used the hands to create unmatched works of art.

THE PREHISTORIC ARTIST

Early man left records in shallow caves, in rock shelters, and, in the great period of art during late Paleolithic times, on the walls of the innermost recesses of caves in France and Spain In the ancient engravings and the wall paintings found in caves in eastern Spain, the

Fig. 7, Famed "Hands of an Apostle Praying," by Albrecht Diirer (A.D. 1471-1528). *Courtesy The Public Library, Washington, D. C.* The original hangs in the Albertina Museum in Vienna.

arms and legs perform animated gestures in running, in drawing a bow, in gathering honey, and in the dance.

The human hand appears in quasi magico-religious silhouettes of complete or partially mutilated hands outlined in color on the walls of the grotto of Gargas in the Pyrenees Mountains. The fingers appear to be cut off at the distal end of the first phalanx, with one or more digits missing entirely. Curiously, the thumb never is amputated. The same type of finger mutilation is found in wall paintings in the caves of central Australia. Apparently the practice was customary among the early Aurignacian people of Paleolithic times, and it also is reported in other preliterate tribes. According to Osborn *(22),* Breuil believes that painting had its beginning in these stencilled contours produced by laying the hands against the limestone walls and spreading red and black paint on the surrounding area. In other examples, the hand was covered with pigment and pressed against the wall.

THE DANCE

The formal patterns and definite movements of the dance make it one of the greatest of the interpretative arts. It is, apparently, also one of the oldest arts. Whether viewed from a recreational, religious, or aesthetic standpoint, this expression of culture has attained meaning and intensity through movement of the hands. Joint dances between the sexes are rare among primitive tribes, and the hand thus has been liberated for gestures and symbolic movements. In India, the hands can tell an entire story. In Australia, among one of the most technologically simple tribes, the movements of the hands make the dance merge into drama. Indeed, it is difficult to separate the dance from music and from drama, but in each of these art forms it is the hand that gives meaning to words spoken. Perhaps the rhythm produced by the hands in clapping and in slapping the body originally led to music and to the dance.

THE HAND IN CULTURE AND SOCIETY

LANGUAGE ABSTRACTIONS

Because the human hand is an organ of performance, it is not surprising that the hand should "manipulate" ("to lead by the hand") the human vocabulary. The hand receives the "mandate" (from Latin "manus," for "hand," plus "dare," "to give") from the brain, and to "manage" is to govern, direct, or control. Thus, man "commends" (which originally meant "to place in one's hands") and "commands," both words related to "mandate" and, therefore, to the Latin "manus," for "hand."

With its basic movements for grasping objects (page *33),* the human hand also is "handy" ("dexterous," "to have two right hands") for grasping ideas. To "comprehend" is to "seize" (Latin, "capere," "to seize"), from which we derive such words as "perceive," "conceive," and "receive." Thus, by various shades of meaning, the human hand not only "hands down" information but "picks" it up. The human hand also is an organ of perception and thus lends itself to the most abstract concepts. "Handsome" originally meant "dexterous." "To feel" is connected somehow with the Greek word for hand, "palame." To say in Latin "dicere" means "to point." We touch, feel, handle,

finger, thumb, paw, grope, palpate, and stroke objects.

ONE AND ONE ARE TWO

Man's hand not only manipulates and grasps, and makes and points, but it counts as well. Counting is very different from what we loosely term "number sense," an attribute that man shares with other animals. In its real connotation, counting appears to be an exclusively human characteristic, and numbers, like so many abstractions, begin with the human body. The old Roman numerals I, II, III, and IIII[4] are thought to be representations of the fingers. In certain of the less well-known languages, the word for hand gives us the word for five. "Five" also has come to mean "hand," and in English the slang expression "give us five" once meant "to shake hands."

One example of the use of hands in counting is that of the Mafulu mountain people, who do not use pebbles or sticks but instead use the hands and feet *(6).* Here counting is accomplished by the use of two numerals, "one" and "two." In indicating "one," the hand first is stretched open to indicate "nothing," the thumb then is closed down meaning "one," the first digit closed down meaning "two," and so on, until all of the fingers of one hand are closed. The process is repeated with the other hand, and, to count to 20, the clenched fist points to the feet and to all of the right and left toes. If the count is above 20 (usually only when important occasions demand, such as counting pigs for a ceremony) another man is called to stand beside the first. If the number goes as high as 83, five men join. Four men go through the entire process, and the last man closes the first three digits.

MAN THE MEASURE

Equally important has been the use of the hand as a unit of measurement. Tables showing the use of body organs as units of measure have been established for volume, surface. width, and length (Fig. 8). The earliest records show that the use of the index finger for indicating length was a widespread custom. In Europe the height of a man was estimated by a definite number of finger lengths based upon the measurement of the middle finger. In Latvia, the length of the middle finger was used to measure lengths for women's stockings or woolen socks (three times the length of one's middle finger). Sixteen times the length of the middle finger equals the normal human stride. The hand and thumb were used to measure width, 12 thumb widths being equal to one foot. Tools were made by the eldest member of the family and adjusted to the hand grasp. Thus, a scythe blade for an adult man was as long as nine or ten widths of the clenched hand, eight for an adult woman, and seven or eight for an adolescent (Fig. 9). The same pattern is found through much of eastern and northeastern Europe today.

SOME TRIBAL CUSTOMS

In the Sun Dance of the Plains Indians of the United States, finger joints were occasionally pledged as a thank-offering for recovery from illness or to ensure revenge for a slain relative *(32).* Cole *(6)* reports that individual warriors among the tribes of Mindanao carried home a hand as evidence of a successful fight and that at such times festivals were held to celebrate the event. Among the Tinguian tribes of the Philippine Islands, joints of the little fingers were added to ear lobes and brains to make a liquor that was served to the dancers. Here, as in most areas of the world, the brew was consumed not for nourishment but in order to secure that part of the enemies' bodies thought to house strength and valor.

Such reports may throw light upon the presence of the mutilated hands found on the walls of the European caves and dating from late Paleolithic times. The scarcity of drawings of the human form in cave paintings may be related in some way to the belief, still found among certain of our "primitive" contemporaries, that realistic portraits might give an enemy magic power. Possibly, through some similar process of sympathetic magic, the hand has already become a symbol to be portrayed realistically in religious ritual.

THE FINGERPRINT

Human hands have been used in various cultures as a means of positive identification.

[4] IV is a later development

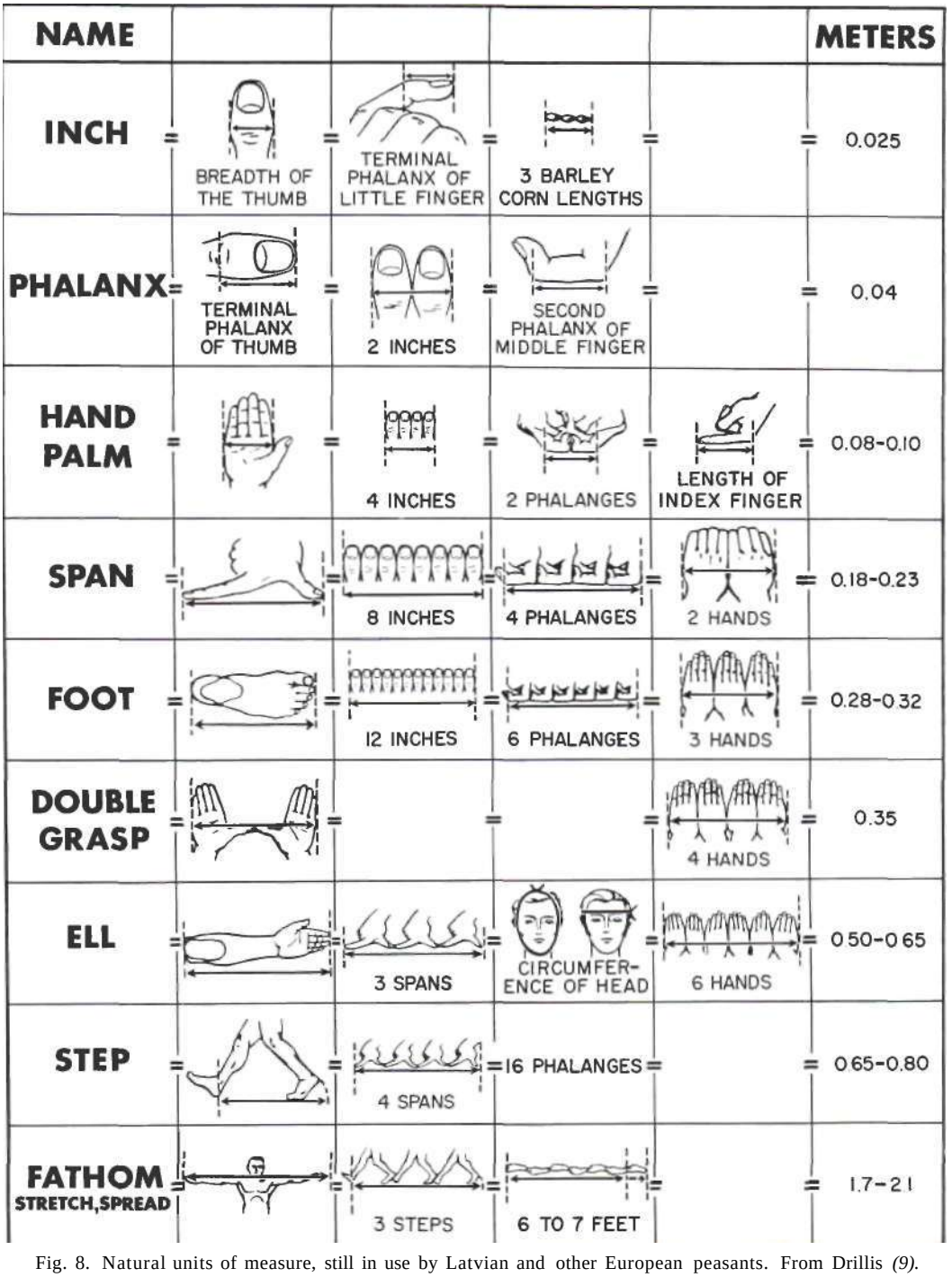

Fig. 8. Natural units of measure, still in use by Latvian and other European peasants. From Drillis *(9)*.

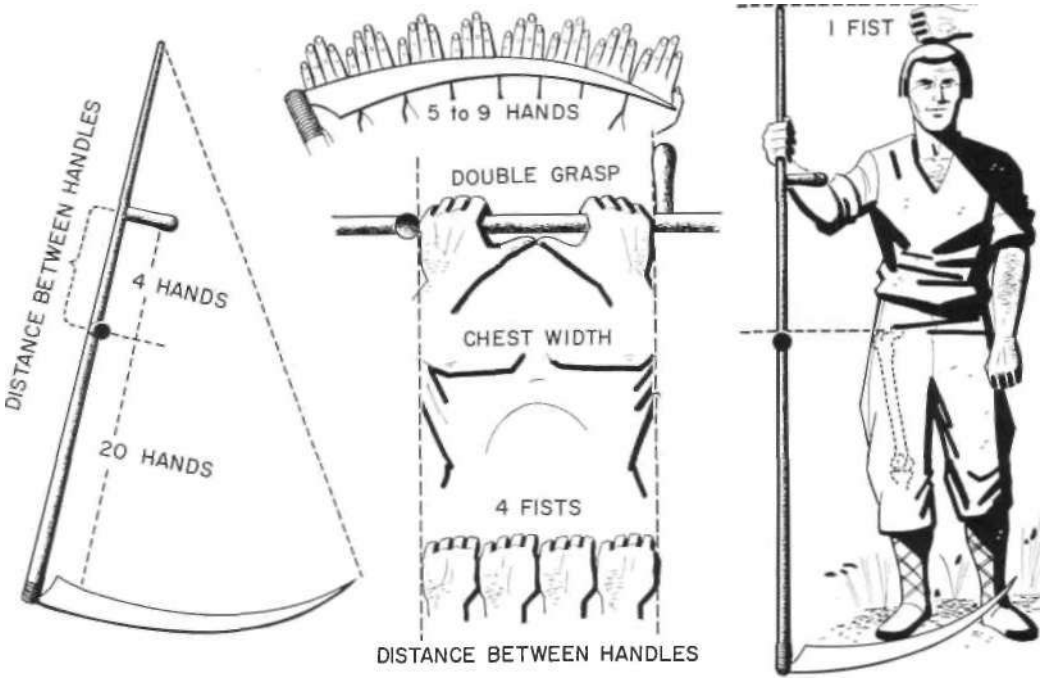

Fig. 9. The method, common among Latvian and other European peasants even today, of arriving at the proper dimensions for farm tools using the hand as the unit of measurement. From Drillis *(8).*

In ancient China, fingerprints were used to sign or to autograph paintings. They are doubly valuable as "signatures" because they cannot be altered or forged, and the intricate patterns of whorls, circular and folded loops, and arches differ from finger to finger and from individual to individual. As the person grows, his individual fingerprint patterns increase in size but do not change in geometric proportions. In 1882, Bertillon, a young French anthropologist, began to develop his famous system for identification of criminals by a physical description based upon eleven anthropometric measurements, deformities, and impressions of lines and markings of the finger tips. The Bertillon system of fingerprints has been used internationally and has proved valuable for physical identification.

SOME OTHER CONSIDERATIONS

OCCULTISM, SYMBOLISM, AND RITUALISM

In an anatomical sense, each hand is unique. Every hand betrays its possessor by characteristic mo/ement patterns, by peculiarities of gesture, or by occupational stigmata arising from physical and mechanical causes. From these characteristics, palmistry and a branch of occultism known as "chiromancy" have, for centuries, attempted to read the past, present, and future of individuals. Since early antiquity, numerous scholars of repute have concerned themselves with studies in palmistry. According to D'Arpentigny (7), Plato, Aristotle, Galen, Albertus Magnus, the Ptolemies, Avicenna, Averroes, Antiochus Tibertus, Tricasso (Fig. 10), Taisnier, Belot, and others have handed down lengthy treatises on the subject, and the observations of these early writers still prevail in our own modern times (Fig. 11). Palmists are interested chiefly in the surface of the hand—lines, stars, crosses, islands—and have divided the life line into seventy parts, each part symbolic of one of man's allotted seventy years of life. Chirognomists study the shape and form of the entire hand, in addition to surface characteristics *(20).*

But it is in the realm of quasi magic and symbolism that the hand reaches its highest

cultural significance. For the great majority of mankind who think in concrete rather than in abstract terms, graphic representations of superhumanity are related to the human body. The Hindu of India symbolizes this superhumanity by the multiplication of the most important parts of the body, which, to him, are the head, the arms, and the hands. Since arms and hands are extremely useful, a twelve-armed god demonstrates the power and the strength denied a two-armed god. Such thinking may appear grotesque to the Westerner, but the Hindu, accustomed to symbolic thinking, knows that man is not so constructed, nor does he wish that he were. He simply recognizes that power and wisdom and strength may be expressed quantitatively *(23).* The Moslem often wears a small image of the hand around his neck to ward off the evil eye.

Fig. 10. Principal lines and mounts of the hand as charted by Patritio Tricasso da Cerasari (Tricassus the Mantuan), a celebrated chiromancer of the sixteenth century. From Lenssen *(18),* by permission of The Studio Publications, Inc., New York City.

Not only in the eastern world does the hand play an important part in the ritual usages but in western culture as well. The pentagram, the five-pointed star, is said to have been derived from an ancient custom of covering the face with the open fingers of the hand. That practice gradually was replaced by invoking the numeral "five," a convention that persists today in countries in central Europe. In Latvia, for example, the pentagram now appears on barns as a protective device.

Finally, the hand has become symbolic of human sentiment. We bless and we salute by raising the hand in various ways. The gentle laying on of hands is at once a symbol of benediction and, as among certain religious sects, the means of curing the sick and of drawing out the evil spirits that reside within the body. In legal practice, oaths are taken in court by the simultaneous use of both hands, right hand up and the left hand on the Bible. We close a bargain by shaking hands, we raise our hands in salutation, and a man takes a woman's hand in marriage. Contrariwise, the hand may express condemnation, malediction, and final judgment. In cursing we point the hand at the enemy. In ancient Rome, thumbs down ("pollice verso") sentenced the gladiator to death. Thus, the hand has become an expository of human sentiment. It can express love, hate, doubt, questioning, hospitality, judgment, rejection, or acceptance.

THE HAND AND GOOD HEALTH

The handshake may become an index to personality and representative of the *whole* person. The cold, limp hand, the strong, firm grasp, the moist palm, the dry palm, all help us to create a mental image of personality. To the trained hand of the physician, the cold, moist, flabby handshake often reveals clues relating to physical condition. Such a handshake often is a symbol of physical illness or an indication of an emotional disturbance. To the trained eye of the doctor the hand tells even more. The coloring, texture, lines, and creases sometimes reveal sickness or health. A trembling, warm, moist hand may mean overactivity of the thyroid, redness may indicate gout, a bluish appearance may indicate a certain kind of heart disease, and bad cases of

malnutrition and diet deficiency frequently are reflected in the hand. There are many variations in the appearance of each hand, but the danger signals can be read only by the skilled hand and eye of a physician.

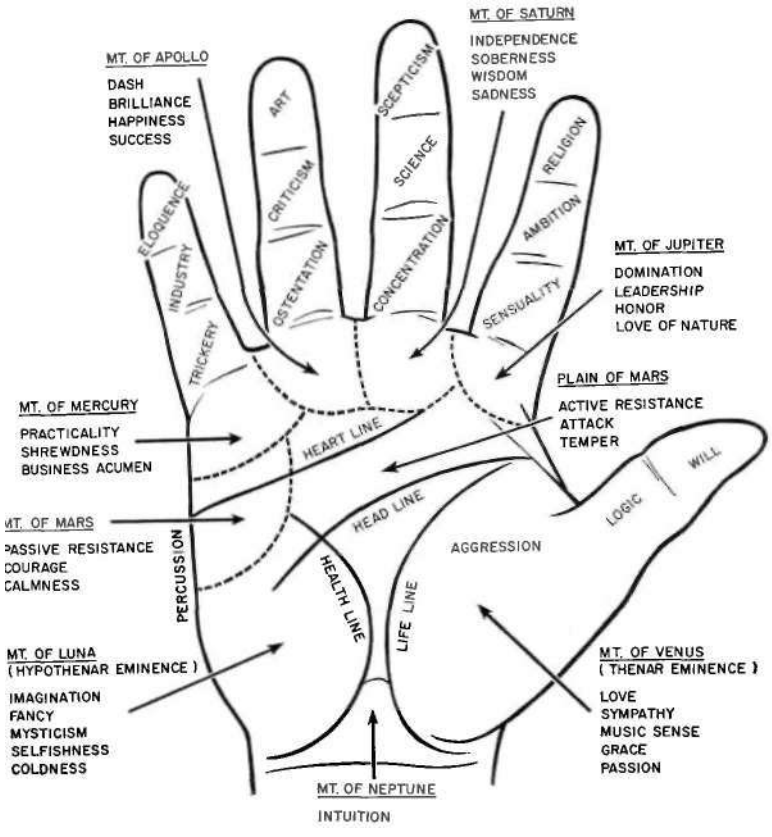

Fig. 11. The mounts and principal lines of the hand and the interpretative functions traditionally assigned to the several areas. Authorities differ in detail, but all follow the same general pattern. In palmistry, which dates from antiquity and which has been the subject of serious discussion by numerous scholars, including Aristotle, the relative development of the mounts and lines is considered to show the comparative ability of the subject to implement the talents and qualities associated with the individual features. Generally the mounts are seven in number, the eighth (Mount of Neptune) occurring in a comparatively small number of cases. Reference to the sun, moon, and planets relates, of course, to the influence which, in early philosophy, these celestial bodies were thought to exercise upon the course of an individual's life. Modern astrology calls upon similar relationships.

THE HAND IN EXPRESSION

The hand has also become associated with certain ethnic and nationality groups, for specific hand gestures have been associated with certain cultural types. Indeed, it has been said of the Italians that they never speak a language, that they caress it. Because movement of the hands serves to emphasize the spoken word, all of us find it difficult to speak while our hands remain perfectly still. A dramatic presentation of the use of the hand in conversation was portrayed through the medium of modern dance in a performance by a group at New York University involving an interpretation of an adolescent talking over the telephone No word was spoken, but the wide variety of gestures made clear to everyone what the performer was saying. The cult and the culture of the "teen-ager" in our country was delineated as sharply through the dance as it could have been through the medium of the written word.

CONCLUSION

From its basic use, prehension, which grew out of anatomical development, the human hand gradually has evolved until it is now also an effective instrument for symbolic and aesthetic interpretation. Man's capable and sentient hand not only serves as a tool but it wields tools as well, and it has in addition the ability to take the place of other body organs. Because of its remarkable adaptability to functional requirements, as compared with the specialization in the forelimb of other animals, the hand is largely responsible for the creative manifestations that characterize the human species and that distinguish it from all

other known forms of life. The hands are, as Kant is reported to have said, "man's outer brain."

ACKNOWLEDGMENT

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LITERATURE CITED

1. Adam, Leonhard, *Primitive art,* Harmendsworth-Middlesex, Penquin Books, Ltd., rev. ed., 1949.
2. Ashley-Montagu, Francis M., *On the primate thumb,* Am. J. Phys. Anthropol., 16(2):291 (1931).
3. Boas, Franz, *Primitive art,* H. Aschehoug, Oslo, 1927. pp. 344, 349.
4. Boyd, William C, *Genetics and the races of man; an introduction to modern physical anthropology,* Heath, Boston, 1950. pp. 16-17.
5. Clark, W. E. Le Gros, *Early forerunners of man; a morphological study of the evolutionary origin of the primates,* Bailliere, Tindall, and Cox, London, 1934. pp. 103-140.
6. Cole, Fay-Cooper, *Lectures,* University of Chicago, 1940-41.
7. D'Arpentigny, C. S., *The science of the hand,* translated from the French by Ed. Heron-Allen, Ward, Lock, and Bowden, London, 1895.
8. Drillis, Rudolf J., *Darba riki [Tools],* in *Lalviesu konversacijas vardnica [Latvian encyclopedia},* A. Gulbis, Riga, 1928-29. Vol. 3, p. 4611.
9. Drillis, Rudolf J., *Mcri [Units of measure},* in *Latvieiu konversacijas vardnica [Latvian encyclopedia],* A. Gulbis, Riga, 1928-29. Vol. 14, p. 26691.
10. Flory, Charles D., *Osseous development in the hand as an index of skeletal development,* Society for Research in Child Development, Monographs, Vol. 1, No. 3, National Research Council, 1936.
11. Hodges, Paul C, *An epiphyseal chart,* Am. J. Roentgenol., 30(6): 809 (1933).
12. Hooton, Earnest A., *Up from the ape,* Macmillan, New York, 1931.
13. Huxley, J., *From fin to fingers: the evolution of man's hand,* Illustrated London News, December 1930. pp. 1138-39.
14. Jones, Frederic Wood, *The principles of anatomy as seen in the hand,* 2nd ed., Williams and Wilkins, Baltimore, 1942.
15. Kahn, Fritz, *Man in structure and function,* Alfred A. Knopf, New York, 1943. Vol. 1, pp. 1515-16.
16. Katz, David, *On the psychology of the human hand,* Bulletin Vol. 32, No. 10, University of Maine Studies, Second Series, No. 14, *The vibratory sense and other lectures,* The University Press, Orono, 1930. pp. 75-78.
17. Krogman, Wilton M., *The anthropology of the hand,* Ciba Symposia, 4(4):1294 (1942). '
18. Lenssen, Heidi, *Hands in nature and art,* Studio Publications, New York, 1949.
19. Mead, Margaret, *el al., Cultural patterns and technical change,* World Federation for Mental Health, UNESCO, Igsel Press, Ltd., Deventer, Holland, 1953.
20. Mierzecki, H., *Symbolism and palhognomy of the hand,* Ciba Symposia, 4(4):1319 (1942). '
21. O'Malley, L. S. S., *Indian caste customs,* Macmillan, New York, 1932. pp. 21-22.
22. Osborn, Henry F., *Men of the Old Stone Age, their environment, life, and art,* 3rd ed., Scribner, New York, 1919.
23. Personal communication from Margaret Cormack, Brooklyn College.
24. Reininger, W., *The hand in art,* Ciba Symposia, 4(4):1323 (1942).
25. Romer, Alfred Sherwood, *Man and the vertebrates,* University of Chicago Press, Chicago, 1933.
26. Romer, Alfred Sherwood, *Man and ihe vertebrates,* 2nd ed., University of Chicago Press, Chicago, 1937. Especially pp. 27-28, 41-42, 363-70.
27. Rosenstiel, Annette, *The Motu of Papua-New Guinea: a study of successful acculturation,* Ph.D. thesis, Columbia University, 1953. Microfilm.
28. Schultz, Adolph H., *Characters common to higher primates and characters specific for man,* Quart. Rev. Biol., ll(4):425-455; ll(3):259-283, 434-437 (1936).
29. Schultz, Adolph H., *The skeleton of the trunk and limbs of higher primates,* Human Biol., 2(3):303 (1930).
30. Smith, Grafton E., *The evolution of man; essays,* 2nd ed., Oxford University Press, 1927.
31. Wilder, Harris H., *A laboratory manual of anthropometry,* Blakiston, Philadelphia, 1920. pp. 84-109.
32. Wiser, Charlotte V., and William H. Wiser, *Behind mud walls,* Harper, New York, 1930.
33. Wolff, Charlotte, *The human hand,* Methuen, London, 1942.
34. Wright, W. B., *Tools and the man,* George Bell and Sons, Ltd., London, 1939.
35. Yerkes, Robert M., *Chimpanzees; a laboratory colony,* Yale University Press, New Haven, 1943.

The Anatomy and Mechanics of the Human Hand

CRAIG L TAYLOR, Ph.D.,[1] AND
ROBERT J. SCHWARZ, M.D.[2]

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

[1] Professor of Engineering, University of California, Los Angeles; member, Advisory Committee on Artificial Limbs, National Research Council, and of the Technical Committee on Prosthetics, ACAL, NRC.

[2] Instructor in Otolaryngology, College of Medical Evangelists, Los Angeles; formerly Assistant in Engineering Research, University of California, l.os Angeles.

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

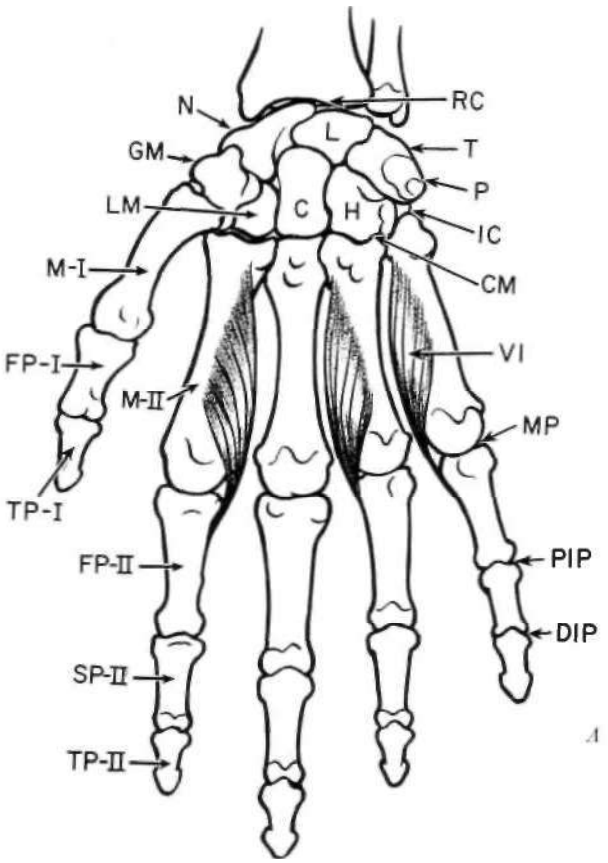

Fig. 1. Bones and articulations of the hand, including the interosseus muscles. *A,* volar view; *B,* dorsal view. For nomencla ture, see Tables 1 and 2.

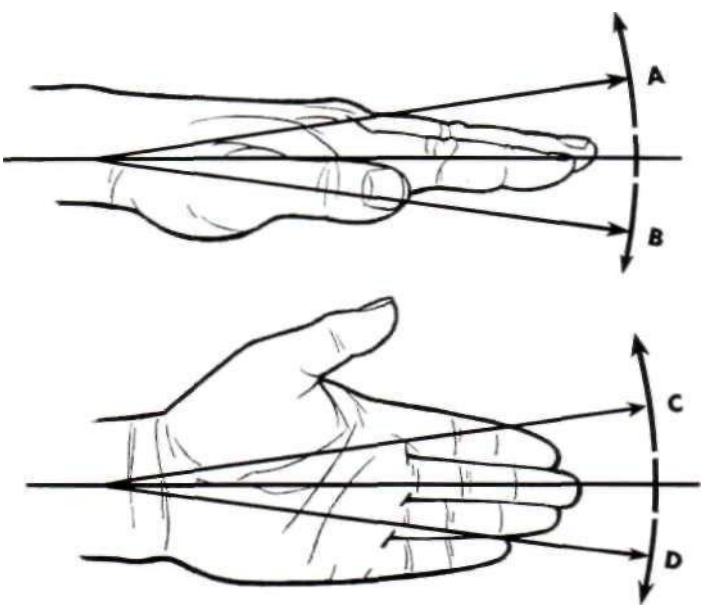

Fig. 2. Angles of rotation about the wrist. *A,* extension (or dorsiflexion); *B,* flexion (or volar flexion); C, radial flexion; *D,* ulnar flexion.

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 (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.

Table 2

MUSCLES OF THE HAND AND WRIST

ADQ,	Abductor digiti quinti
AP,	Adductor pollicis
APB,	Abductor pollicis brevis
APL,	Abductor pollicis longus
APO,	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

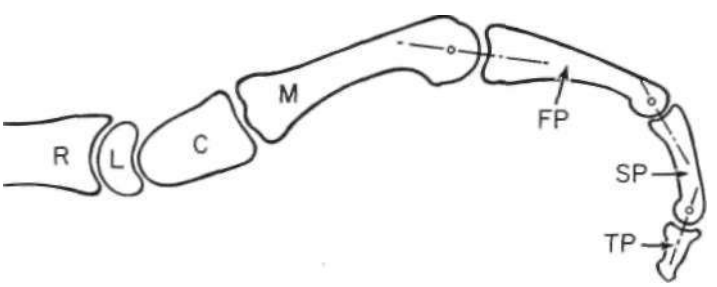

Fig. 3. Section through radius, lunate, capitate, and the bony structure of digit **III,** showing virtual centers of rotation of each segment upon the next more proximal one. When the fist is clenched, the prominence of the knuckles is formed by the head of the more proximal member of each articulation.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

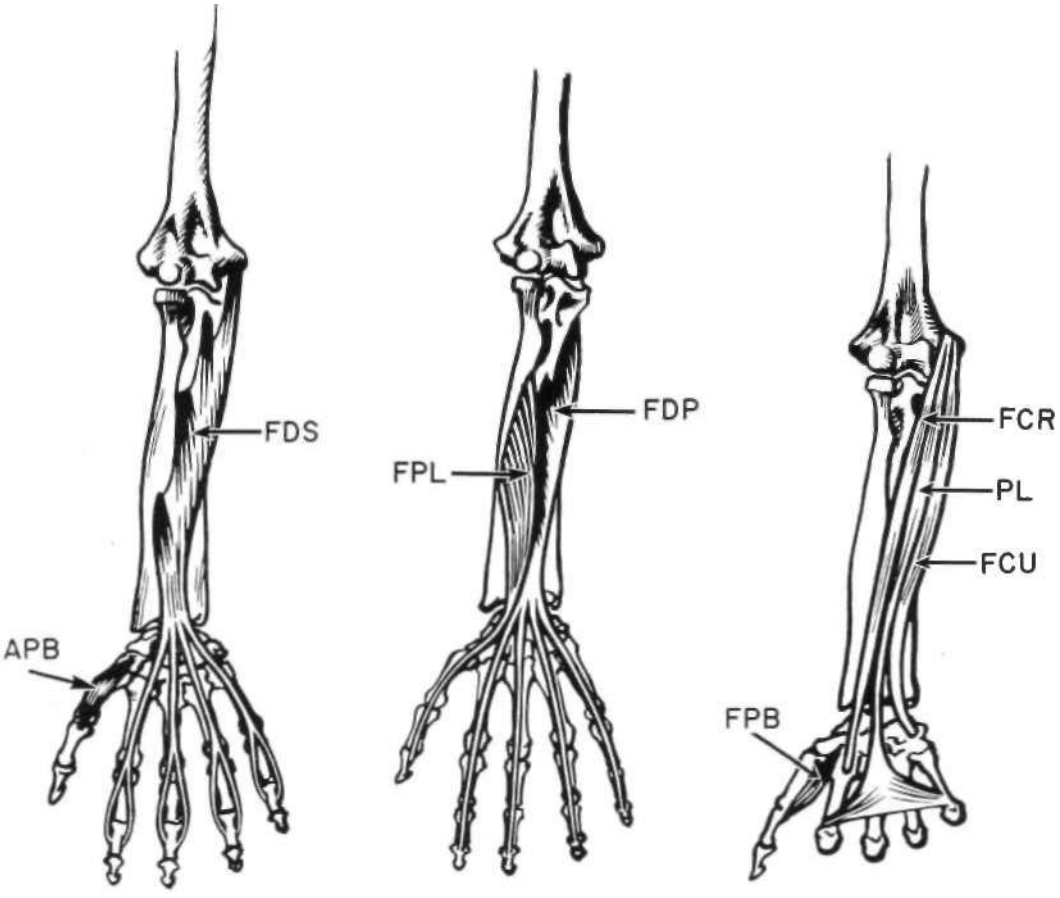

Fig. 4. Flexors of wrist and digits. For nomenclature, see Table 2.

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.

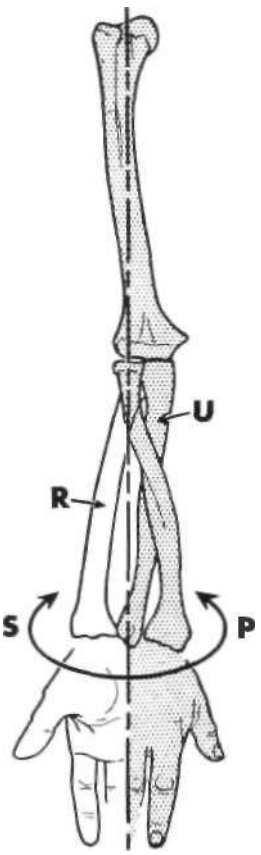

Fig. 5. Forearm design as related to hand mobility. By virtue of this arrangement, the hand can be rotated through 180 deg., palm up to palm down, with the elbow flexed. With the arm fully extended, participation of shoulder and elbow allows the hand to be rotated through almost 360 deg., palm up to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

The 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.

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.

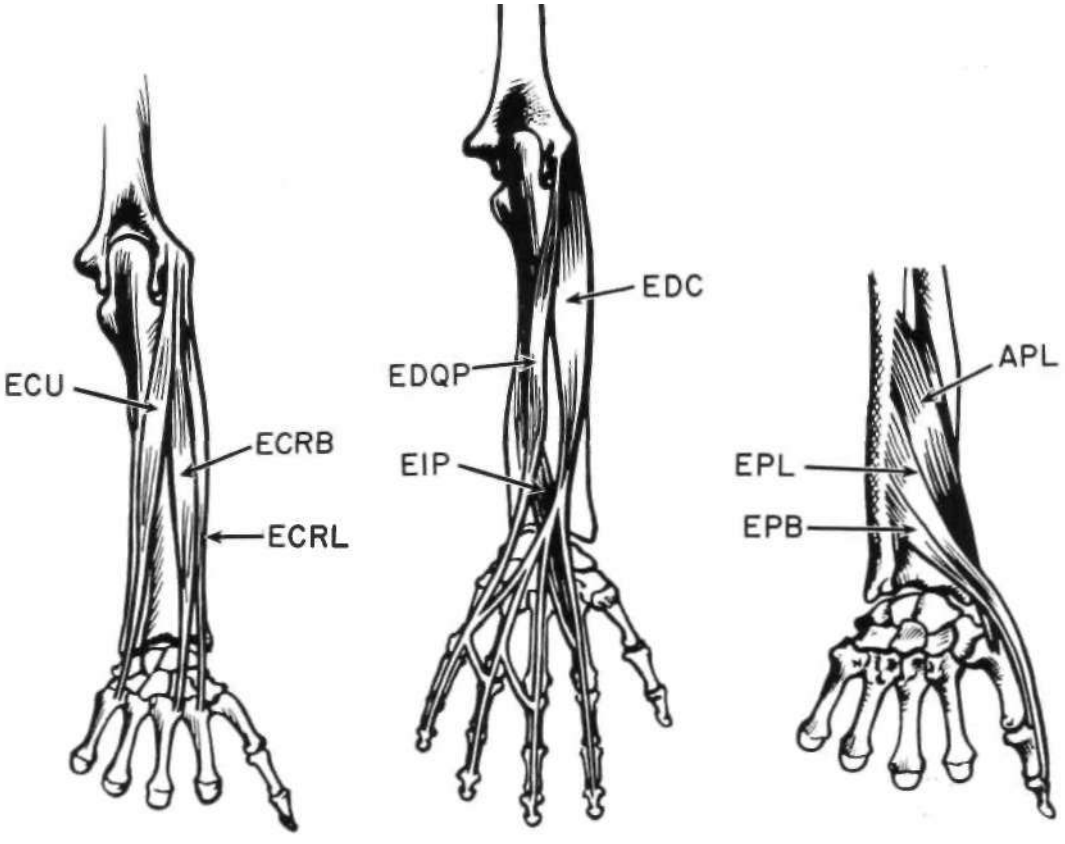

Fig. 6. Extensors of wrist and digits. For nomenclature, see Table 2.

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."

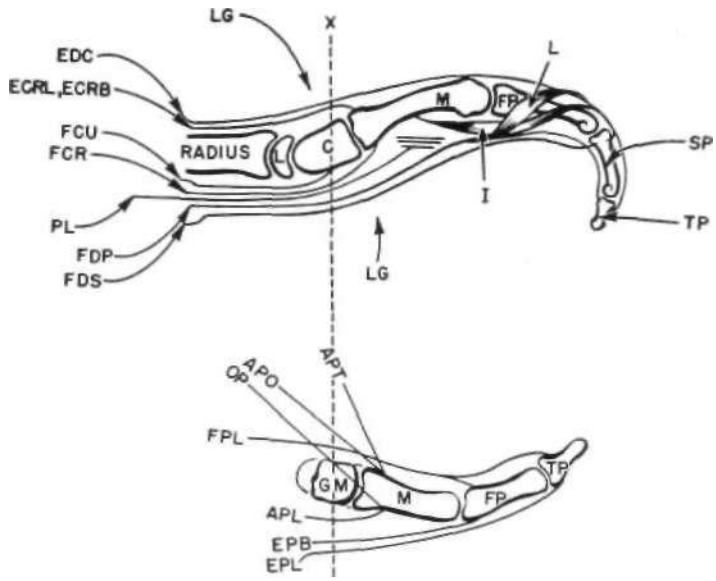

Fig. 7. The anatomy of prehension. Schematic sections through digits I and III show essential relations of muscles and bones. The letters *LG* indicate the presence of ligamentous guides which channel close to the wrist the tendons of muscles originating in the forearm. Guide line X—X indicates relative 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, rotating 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

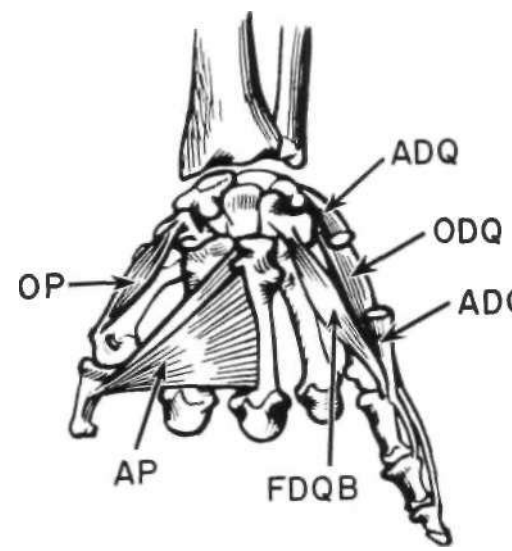

Fig. 8. Volar intrinsic muscles of the hand. For nomenclature, see Table 2.

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.

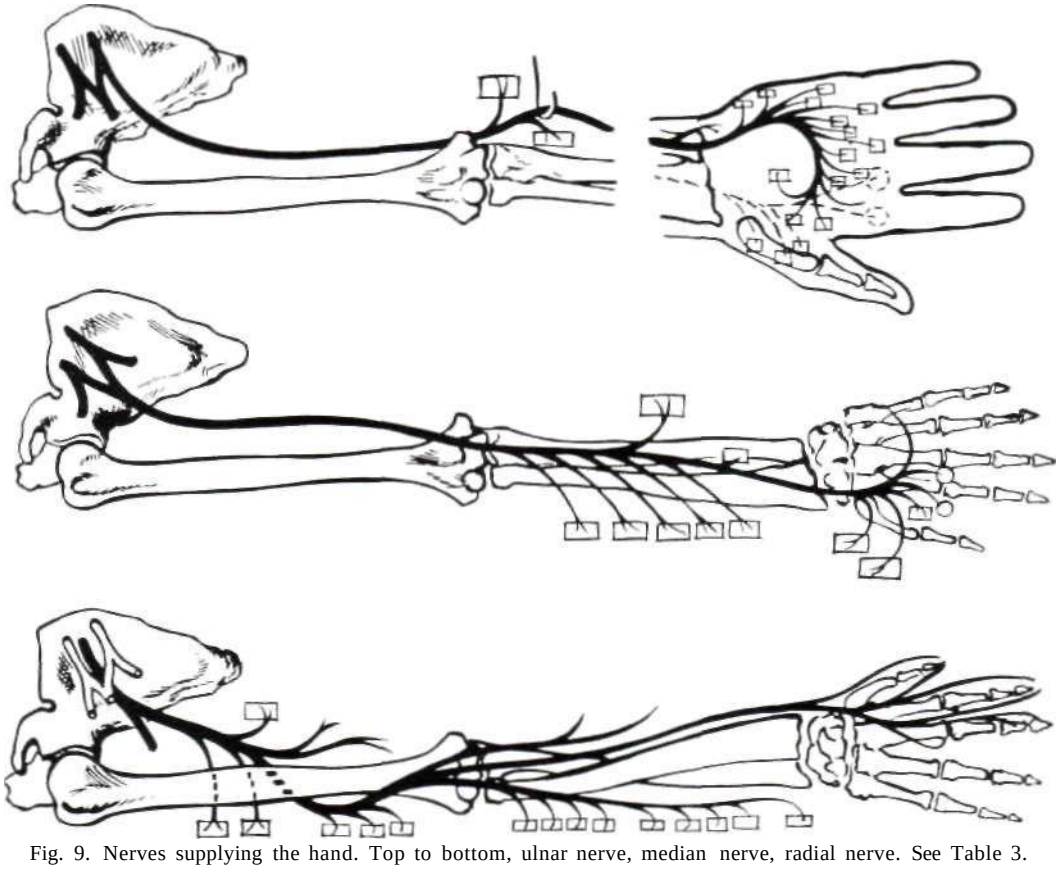

Fig. 9. Nerves supplying the hand. Top to bottom, ulnar nerve, median nerve, radial nerve. See Table 3.

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.

[a] From Fick (7).

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

[c]Averages 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).