The Principles of Artificial-Hand Design

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To REPLACE with a fully adequate substitute any living organ as complicated and as finely fashioned as the human hand is long apt to remain a virtually impossible task. The designer of hand prostheses must therefore accept at once the pre-established circumstance that, in any model he is likely to produce, he will be faced with the simulation of the infinite mobility of the natural hand but at the same time will be lacking the power sources, nervous sensitivity and subconscious reflexes evidenced in the natural mechanism. Since "hand replacements," even if possessing some anthropomorphic features, can scarcely be viewed as replacements in fact, they are inherently destined to have only the characteristics of tools designed to extend the usefulness of an arm stump.

Because in the present state of the art it is quite impossible to incorporate into a hand prosthesis more than a very limited number of the attributes of the normal (page 22), limb designers have always been called upon to select, from among all normal hand characteristics, those features whose loss is most seriously felt by the arm amputee. Among these, of course, are prehensile function, sensory and perceptual ability, and the cosmetic appearance of the hand itself, generally in that order of importance even in the unilateral below-elbow case and usually in the female as well as in the male. In almost all cases of upper-extremity amputation, the inability to grasp objects is the deficiency most keenly felt, and in bilateral cases the patient is thus rendered virtually helpless except insofar as other parts of the anatomy—particularly the stumps, the teeth, and the lower limbs—may adapt to some of the former functions of the hands.

Except in unusual cases, it is a comparatively easy matter to provide substitute prehension, for the several patterns of normal grasp (page 33) are all seemingly variations of a basic pincer action. This accounts for the more or less obvious development of the split hook, in a great variety of designs (page 72), to be powered by scapular abduction, arm flexion, cineplastic muscle motor, or other sources of force and excursion working in opposition to springs or rubber bands *(6,7,15,19)*. By virtue of its adaptability as a tool for a great many different kinds of activity, and with no serious limitations in form and appearance, the hook prosthesis has had a long period of yeomanship in the service of thousands of arm amputees.

Just as replacement of a basic, if crude, prehensile function offers the engineer no real problem, so also is it comparatively simple to fabricate a nonfunctional but realistic artificial hand. Thus reasonably faithful, passive hand replicas have been available for some time past. But to provide both hand form and hand function in one and the same hand substitute is an infinitely more difficult task. For reasons of limitations of power sources, of space for mechanisms, of available materials, of finger design, and of other matters, cosmetic appearance usually has been obtained only at the expense of functional adequacy, and vice versa. This circumstance accounts in part for the past popularity, still widely persisting, of hooks among arm amputees generally. Because such

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artificial hands as existed heretofore were either functionally deficient or cosmetically poor or both, a great many arm amputees found them more bother than benefit.

Although sensory perception may be considered by many arm amputees to be next in importance to prehensile function, it is unquestionably the one feature most difficult to provide in a hand substitute. If, to prehension and hand form, there be added the requirement of sensory perception at a reasonably satisfactory level, then the design of successful hand substitutes is again obviously complicated manyfold. That this is so is reflected in the fact that, for sensory control, the upper-extremity amputee even at the present time has still to rely on a combination of visual reception, audible clicks of various kinds purposely built into operating mechanisms, and a set of secondary neuromuscular cues to be obtained from shoulder harness, cineplastic muscle tunnels, pressure of the socket on the stump, and so on.

The normal hand has the inherent ability to relay, with no external assistance from the other senses, information about the shape, form, texture, and general physical condition of objects grasped. It can sense when contact has been made and what gripping force is in effect, and it has in addition an elaborate control mechanism with the ability to modify the force of grasp automatically as required to adjust for slipping or crushing. Besides this, the natural hand can report unassisted its own orientation in space. Present hand substitutes have no such self-contained attributes. Direct sensory control in either hook or artificial hand remains as a major challenge for the future in upper-extremity prosthetics.

Despite these recognized limitations, some very sound reasons can be set forth as to why hand design, as contrasted with hook design, deserves increasing emphasis. In comparatively recent studies with an improved functional hand *(12),* it has been shown that a great many more arm amputees prefer a hand over a hook when the two are of reasonably comparable usefulness. Although it seems unlikely that the manipulative characteristics of artificial hands will any time soon attain the functional level possible in hooks, and although many amputees will no doubt continue to prefer hooks for many activities, there is a growing body of evidence that numerous patients would, for a number of reasons, prefer a functional hand for many occasions and, indeed, for a steadily increasing number of occupational pursuits. The data clearly suggest that the more realistic *and* functional a hand substitute can be made the more and the more often do amputees, and the general public as well, prefer artificial hands over the most pleasant-appearing hooks *(12).* In these circumstances, earlier work in the Artificial Limb Program aimed at improved terminal devices *(7,19)* has been continued with increasing attention to the requirements of successful artificial hands. Out of this work has now come a set of design criteria based on fundamental investigations conducted largely at the University of California at Los Angeles and at the Army Prosthetics Research Laboratory.

THE REQUIREMENTS OF HAND DESIGN

The first and very obvious requirement placed upon the designer of a satisfactory artificial hand is that the exterior configuration must be such that the device cannot readily be distinguished from the natural hand. This limitation involves not only size and shape but external surface characteristics as well. Thus the second matter to consider is the method to be employed in arriving at lifelike appearance.

Within the limitations imposed by these two requirements, and considering the available sources of power and control, a choice must be made of the functions to be provided. How these functions had best be performed then requires adoption of a plan of digital mechanics that is operable within the limitations already established.

Finally, because so few sources of power are available for operation of upper-extremity prostheses, it is generally agreed that not more than one source should be diverted to hand operation. Because muscles are capable of producing tension only, the designer is faced with the fact that power from any single body source can be applied in one direction only. Thus, in the present state of development, power may be applied either to opening or to closing, but not to both.[3]

THE PROBLEM OF HAND SIZE

Careful observation reveals that the human hand varies greatly in size and shape from person to person and even within the same person. Hence it is clear that, if the hand requirements of the amputee population are to be satisfied, a spectrum of sizes of artificial hands has to be provided. How extensive the size range needs to be depends upon a number of factors. Since the custom design of individual hands for individual amputees, though possible, leads to high costs, and since in any case it has been shown *(13)* by Dembo *et al.* (page 47) that casual observers rarely detect small differences when objects approximate the appearance expected, it is first necessary to determine the minimum number of hand sizes that will provide an acceptable match for the natural hand of most unilateral arm amputees and that in the bilateral case will furnish a hand somehow "compatible" with body size.

But the problem of hand sizing is a subject that has generated more heat than light and one that is replete with pet theories. One reason for this situation is that the matter of hand sizing is extremely complex and subjective and that the factors contributing to size and appearance appreciation are elusive and undefined. It has been observed, for example, that two plastic hand models having precisely the same dimensions may, by varying the hand attitudes, be made to appear different in size. Furthermore, in a sequence of hand models of decreasing size, relocation of a model in the sequence, or changing its distance from its nearest neighbors, may seem to cause a change in its apparent size. Other factors, such as shape, skin detail, texture, knuckle and vein characteristics, and color, may contribute to over-all apparent size and appearance.

Various combinations of these factors lead to such generic terms for describing hands as "masculine" and "feminine" and to such specific adjectives as "large," "small," "stubby," "smooth," "gnarled," "bony," "graceful," "awkward," and so on.[4] The problem of hand sizing is therefore twofold—one relating to actual sizing, which may be described by numbers, and the other to appearance attributes, which may affect the apparent size but which presently are not amenable to quantitative description. In any case, the number of hand sizes to be provided is dictated by the distribution of sizes in the hand universe, by the closeness of the match desired, and by the commercial feasibility of supplying a given number of hand sizes.

Surveys of Hand Sizes

The first survey to size the prosthetic hand for male adults was made by Birdsell *(4)* of the University of California at Los Angeles. Undertaken from the viewpoint of the anthropologist, it was detailed and complete, some 26 hand dimensions of approximately 100 adults being reported. But the results indicated that the major dimensions (Fig. 1) showed a low degree of correlation. For example, a correlation coefficient r — 0.50 was obtained for hand length vs. hand breadth. This being the case, a single, basic hand dimension—hand breadth—was chosen, and all other measurements were regressed against hand breadth regardless of the size of the correlation coefficient obtained. By use of these methods, a systematic sizing schema was set up for the male adult hand.

From the adult mean values for hand

[3] Springs have generally been employed to provide the return action. Cineplastic muscle tunnels have been provided in the flexor and extensor muscles of the forearm in an effort to furnish powered operation in both directions, but these muscles inherently are lacking in sufficient force and excursion to provide adequate prehension *(3).* Furthermore, such an expedient would solve the problem in the wrist-disarticulation and long-below-elbow cases only The prospects now seem good that unidirectional power soon may be applied successfully both to opening and to closing. For a discussion of the so-called "reflex hand," see page 90.

[4] In the popular concept, perhaps the distinguishing differences between feminine and masculine hands relate to size, shape, and, possibly, to fingernail length. But as a matter of fact women's hands may be large or small, long or short, gnarled or smooth, graceful or awkward, and generally may have as prominent skin detail and knuckle and vein characteristics as those usually ascribed to men's hands.

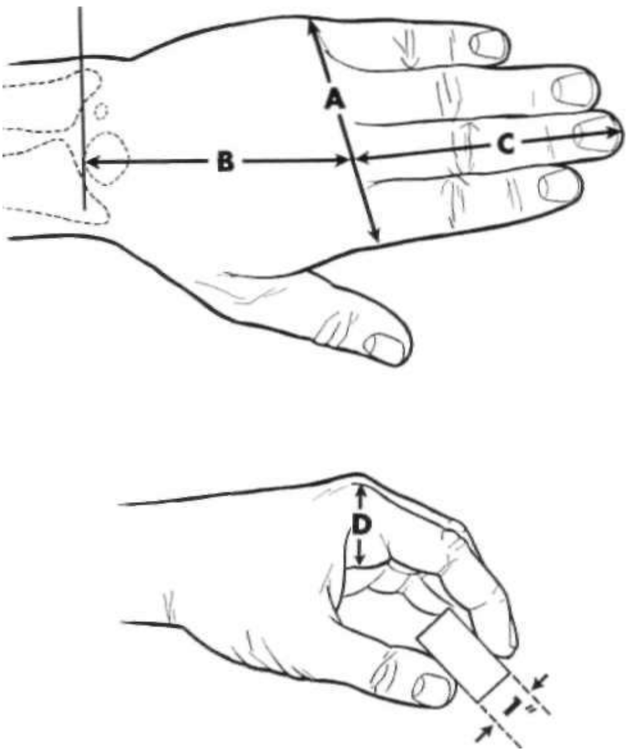

Fig. 1. Principal dimensions used in the study of hand sizes. After Birdsell *(4)*. Dimension *A* is hand breadth measured from the radial aspect of the second metacarpal head to the ulnar aspect of the fifth metacarpal head. Dimension *B* is dorsum length measured from the center of the proximal side of the lunate to the apex of the metacarpophalangeal joint of the third digit. Dimension C is the middle-finger length measured from the apex of the third metacarpophalangeal joint to the end of the third digit. Dimension *D* is the palm thickness.

breadth, dorsum length, middle-finger length, and palm thickness, taken from the Birdsell data, Gottlieb (8) calculated the ratios of hand breadth to hand length, dorsum length to hand length, middle-finger length to hand length, and palm thickness to hand length. The assumption, later proved not to be completely justified, was made that these ratios do not vary as a function of age, and, from previously published data *{14,18)* concerning juvenile hand length, Gottlieb was able to calculate average values for the various required dimensions of artificial hands for children.

In September 1954, DeFries (5) of the Army Prosthetics Research Laboratory, using the data of Birdsell for the adult male population, applying new hand-sizing data gathered by measurement of adult female hands and hands of children in the age groups 4 to 6 and 10 to 11 years, respectively, and using some of the methods suggested by Gottlieb, reported a sizing schema for prosthetic hands to satisfy the amputee population from children to adults. In Figure 2, which presents the distribution of hand breadths by population group, there is some overlapping between the large adult female hand and the small adult male hand, as well as between the large hand breadths of children in age group 4 to 6 and the small hand breadths in the age group 10 to 11. Similarly, there is a striking overlap between hand sizes of the adult female group and of the children 10 to 11 years old.

Number of Sizes Required

The target sizes for hand breadths of natural hands are indicated below Figure 2 by arrows pointing downward. The numbers of targets and their position in the distribution of the hand universe were selected by considering such factors as differences in hand breadths between normal pairs of hands, the number of amputees to be fitted by a given hand size, the rate of growth of natural hands, the importance of cosmesis within a group, and the commercial feasibility of supplying prosthetic hands in a number of sizes. Below the target sizes for the proposed hand breadths, indicated by arrows pointing upward, are the sites of the proposed prosthetic hand breadths. These represent the selected hand breadth of the natural hand less a factor designated as the "prosthetic illusion factor," an arbitrary number which is subtracted from the breadth of the natural hand. It is included because, from hand-fitting experience and impression rather than from systematic study, it is found

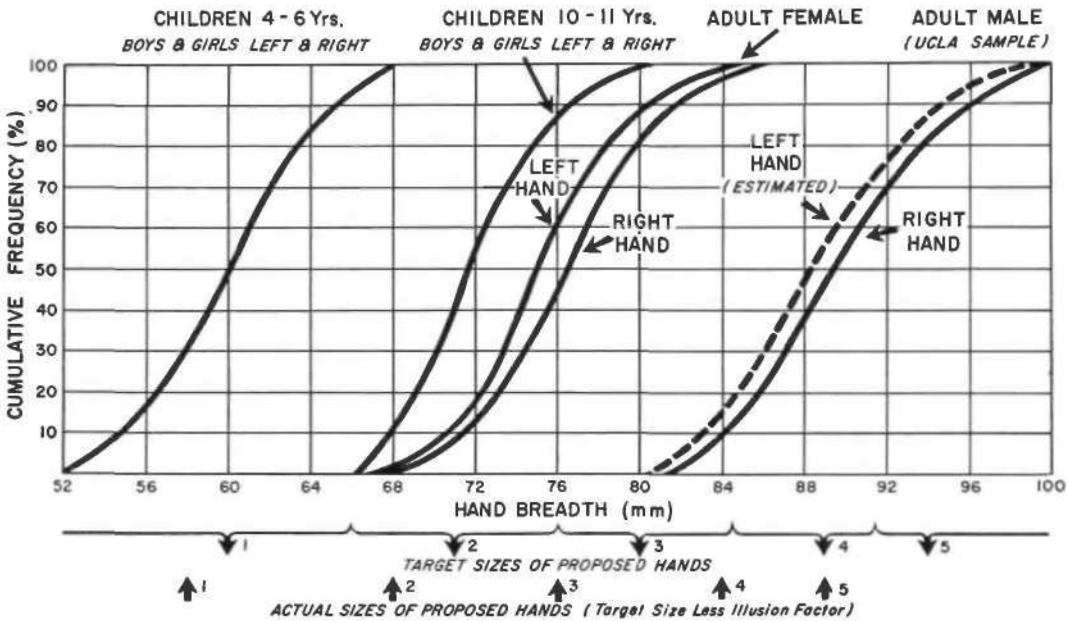

Fig. 2. Distribution of hand breadths by population group. After DeFries (5).

that for best results the prosthetic hand should be from a half to one and a half glove sizes smaller than the hand it replaces *(4).*

When the selected hand-breadth values are multiplied by the appropriate ratios of average middle-finger length to hand breadth and of dorsum length to hand breadth (Fig. 3), the desired dorsum length and middle-finger length are obtained, and the dimensions for five hand sizes may be detailed. It is interesting to note (Fig. 3) that the ratios of middle-finger length to hand breadth and of dorsum length to hand breadth increase with increasing hand breadth, indicating that adult hands have a tendency to be longer and narrower, children's shorter and wider, a result in accord with general observation and experience.

Construction of the Models

The determination of the required dimensions represents, of course, only a very early, toddling step toward the goal of achieving the five hand sizes. The next step is the construction of the physical models so that not only size but also shape and skin texture may be visually examined to compare subjective impressions. From experience with commercially available voluntary-closing hands and with experimental models, it is believed that optimum cosmetic shape is obtained if the hand shells are cast from the corrected impressions of living models. The problem, then, is to find a suitable, living hand model with the required attributes of size, shape, texture, and detail. Since the dimensions specified represent population averages, it would be fortuitous indeed to find living models whose hands had precisely the required dimensions in addition to the other appearance attributes.

Fortunately, techniques have been developed for making necessary adjustments in both size and shape after the original impression has been taken, thereby simplifying considerably the task of finding the model. Once a model is found to have the desired texture and approximate size, gross size changes may be made by solvent extraction of plasticizer from plasticized polyvinyl chloride films. This process was worked out in the laboratories, and inert but accurate hands (Fig. 4) were made for optical appraisal by a large group of experts in the prosthetics field.

THE PRODUCTION OF COSMETIC APPEARANCE

Over-all hand size is not the only measure of how large a hand mechanism may be, for the problem of producing satisfactory cosmetic appearance introduces another factor. It is difficult to conceive of a finish for metal, or other material hard enough and strong enough for an artificial hand, that would impart to the observer the texture, depth, variation in color, and other properties of the human skin. Experience teaches that the only practical means of attaining satisfactory cosmetic appearance is to cover the hand structure with a glove of some material which simulates the human skin both in texture and in color (page 57). Techniques have been developed for the manufacture of such gloves from plasticized polyvinyl chloride *(11).*

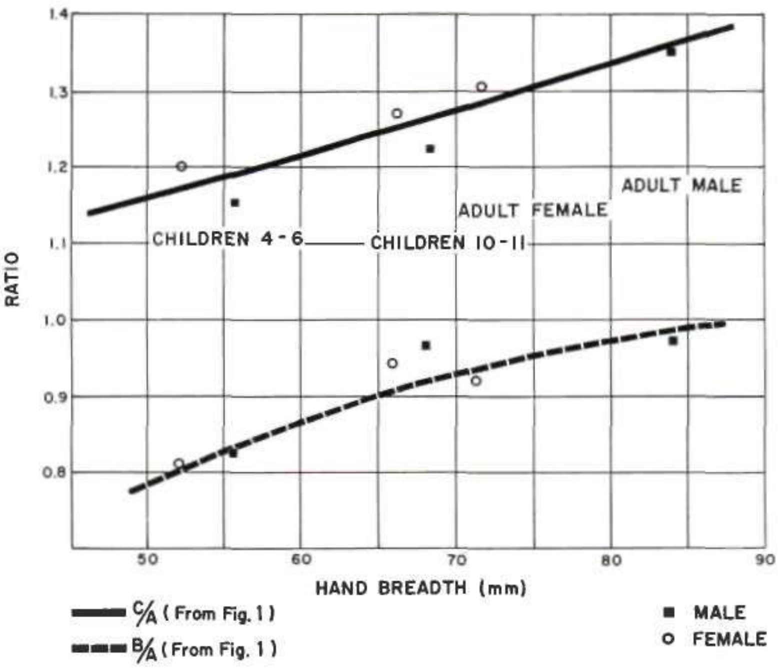

Fig. 3. Ratio of middle-finger length to hand breadth and of dorsum length to hand breadth from age four to maturity. After DeFries (5).

But the thickness of the glove material is dictated not only by physical properties such as tensile strength, elasticity, and resistance to snagging and tearing but also by the fact that the coloring is influenced by the thickness of material through which the color is viewed. A smooth-fitting glove must stretch when the hand flexes, and it has been established that ideally the force requirement due to stretching of the glove shall not be more than 1 lb. over that needed to flex the uncovered hand. Thus a successful glove must be comparatively thin. Yet it has been found that proper depth and other properties of lifelikeness are to be obtained only by tinting on the *inside* of the glove so that the color is observed through a thickness of the material *(11).* At present, optimum glove thickness is considered to be about 0.03S in. Thus the hand housing must be that much smaller than the over-all hand size desired.

DESIGN OF THE HAND SHELL

If a single hand design is to be provided for all upper-extremity amputations, then, in order to accommodate the long-below-elbow and wrist-disarticulation cases, it is necessary to provide within the hand sufficient space for a mechanism or mechanisms.[5] But the forces involved in the hand are high compared with the size of the device, while at the same time space is extremely limited. Maximum volume for the installation of mechanisms within the hand can best be achieved by employing a thin-walled, hollow casting of the palm section (Figs. 5 and 6). Light alloys such as those of magnesium and aluminum have been employed successfully in this application using the investment-casting technique. Sufficient rigidity for the forces involved can be obtained in aluminum with a wall thickness of 0.035 in. Thus the net space available for mechanisms is the gross size of the hand less the thickness

[5] For amputation at other levels, mechanisms might be installed in the prosthetic forearm.

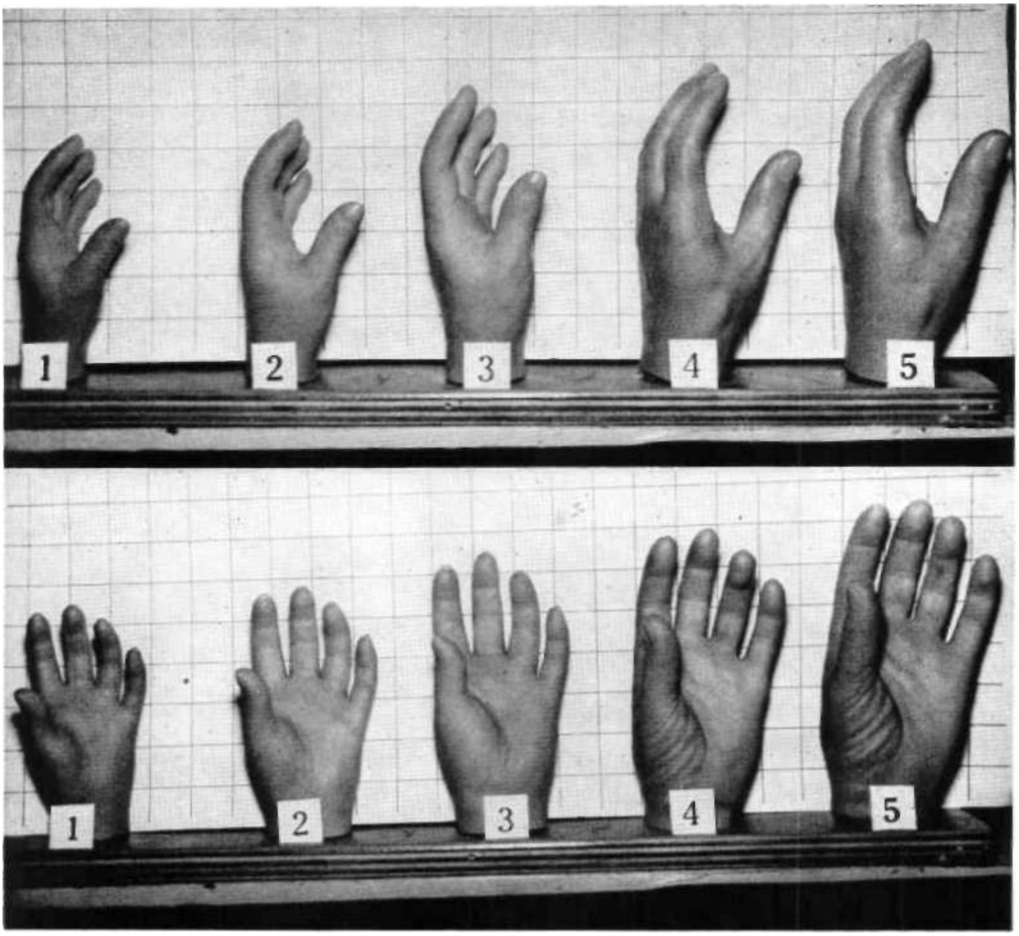

Fig. 4. Prototypes of the five hand sizes required to satisfy the population from age four to maturity. *Courtesy Army Prosthetics Research Laboratory,*

of the cosmetic glove less the thickness required in the hand shell.

Accordingly, after the hand models have been reviewed both objectively and subjectively, appropriate corrections are made, and electroformed molds are constructed and reduced by the thickness of the cosmetic glove. The molds then are cut on pre-established lines, again corrected for the mechanical considerations by establishing pivot bosses for the mechanism, assembled, tested for natural movement

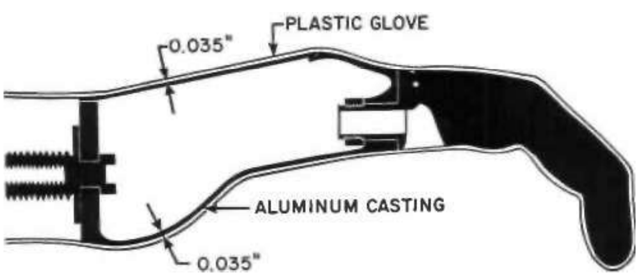

Fig. 5. Section through palm and middle finger of an artificial hand of monocoque construction. The technique of investment casting keeps the thickness of the hand shell at a minimum and thus provides maximum space for operating mechanisms

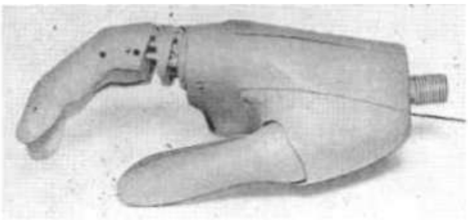

Fig. 6. Experimental hand with palm section of monocoque construction. The finger design shown, also experimental, is one of many tested. See Figures 9 and 10. *Courtesy Army Prosthetics Research Laboratory.*

and coordination with a glove, and used as patterns for the final castings at the foundry. The original molds from each of these hands are used as master molds, and duplicate or "use molds" are electroformed for production of the cosmetic glove, which will then fit the finished hand mechanism precisely.

PROBLEMS OF POWER AND CONTROL

Once the required sizes have been established for the hand shell, attention must be directed toward the choice of source of power and control because design of hand-operating mechanisms is clearly influenced by the amount of power and excursion available. Since certain levels of force are required in the prehensile mechanism, and since input and output are related through the mechanical features of the hand itself, the nature of the control forces must be known before mechanisms can be designed.

At first thought it would seem a comparatively simple matter to simulate all the articulations represented in the metacarpal bones and the phalanges of the natural hand. One might then reasonably expect such a device to perform many of the functions of its normal counterpart. But all such attempts have ended in complete failure, chiefly not for want of adequate structural and mechanical details but for lack of a sufficient number of workable controls *(15).* The normal hand is powered by some 24 separate but highly coordinated muscle groups controlled by an elaborate pattern of nerves emanating from the brain (page 22). Because the motions of the normal hand are controlled automatically as though by reflex action, little conscious effort is required to manipulate the hand or fingers into positions of utility. In the arm amputee, "mind-controlled" power sources and nerve supplies are seriously reduced. Hence it is necessary to find for a prosthetic arm and hand a source of power and excursion that involves only simple operating motions but at the same time provides the forces necessary for adequate prehensile function.[6] When the power available to the arm amputee is analyzed, it is found that, except for cineplasty *(3)* and external power such as electricity *(1,2,9),* no more than one useful hand power source is available—and that operable in one direction only *(15).*

Sources of control should therefore be so chosen as to eliminate unnecessary exertion and undue bodily contortion in using the artificial hand. In current practice, scapular abduc-

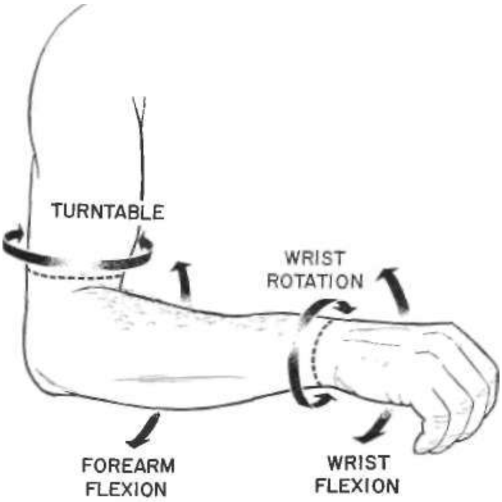

Fig. 7. Basic features of the arm as a device for positioning the hand.

[6] In order for a hand to perform its functions, it must of course be placed in position, and positioning of the hand requires some type of suspension. A satisfactory artificial arm should involve a minimum number of motor sources but should be capable of the movements needed to place the hand in position for grasping an object. If such an arm is equipped with an active elbow, a lock for stabilization of the elbow, a turntable for positioning the forearm laterally, and a wrist unit for positioning the hand in flexion and rotation (Fig. 7), it should meet the requirements of an efficient "crane."

tion provides a satisfactory major source of control. It can be used to best advantage when coupled with humeral motion on the amputated side. Where such is the case, the opposite shoulder is used mainly as an anchor point, arm flexion providing the force and displacement required to operate the terminal device *(15,17).* Considering the limitations of available motor sources for hand function, and the desirability of complete independence of the artificial hand from the other hand, whether that hand be normal or artificial, it is clear that, for simplicity and ease of operation, input control should be a single control requiring but one cyclic motion.

Because it is desirable that the hand be suitable for the majority of arm amputees, it is necessary to determine the excursion and power available for hand operation by the weakest amputees, and at the same time the hand mechanism must be stressed for the forces that might be exerted by the strongest amputees. Thus, extensive biomechanical studies are necessitated in order to establish the minimum and maximum limits of motion and forces available *(10,15,16).* Analysis of the resulting data shows that an arm amputee should be able to grasp with a force of at least 15 lb. objects of all sizes and geometrical shapes up to about 3 in. in diameter. Minimum anticipated available work is calculated to be 37.5 in.-lb. or l-1/2 in. of excursion with 25 lb. of force. This condition means that the designer should strive for an over-all output-to-input ratio of 0.6 for hand and control system.

THE CHOICE OF DIGITAL MECHANICS

Once the lower limits of the available motor input are established, it then becomes necessary to determine which hand function or functions this force is to provide. To do so requires a complete survey of hand biomechanics, including accurate, detailed studies of the uses of the hand, the finger forces necessary to accomplish myriad tasks, the frictional characteristics of the skin, exact finger attitudes, approach to the object to be grasped, and the stability of the grasp on objects of various geometrical shapes.

In the natural hand nearly every segment is capable of stabilization by antagonistic muscle groups, thus affording a fixed base upon which flexion or extension of the next distal segment can be produced. Because such an arrangement in an artificial hand would require a multiplicity of controls, it would be very difficult, if not impossible, to simulate the natural plan of digital mechanics. Designs of artificial hands incorporating all phalangeal segments, but with a single coupled flexion system omitting the multistabilization feature of the natural hand, have been uniformly disappointing. Consequently, all differential digit motions, all variations in thumb opposition but one, and all distal phalangeal joint motions may have to be sacrificed.

Type of Prehension

From the intricate and varied function possible in the normal, then, there must be selected a single action pattern similar to that type of prehension used most frequently in everyday activities. To make such a selection requires fundamental study of hand prehension patterns in normal subjects (Fig. 8). On the basis of such investigations, it is possible to list the most common and most essential manipulations of the hand in relation to objects to be handled, including such activities as opening various types of door locks, dialing telephones, using eating utensils, writing, combing the hair, dressing, carrying various objects, and a host of other functions *(10).* When the data thus accumulated are reduced to a frequency chart, it is found that the basic prehension type most used involves closure of the first and second fingers against the thumb in a three-jaw-chuck pattern known as "palmar prehension" (page 33).

In the normal hand, the third and fourth fingers act mostly as reinforcing agents, as a resting shelf for holding certain objects, and as gliders in activities such as writing. When, however, sensation has been lost, the third and fourth fingers interfere with the normal approach of the first and second. In the artificial hand, therefore, they are necessary only for cosmetic purposes and should yield so as not to interfere with the approach of the active fingers. The output utility of the hand thus may be considered as residing in the thumb and first and second fingers, and the next

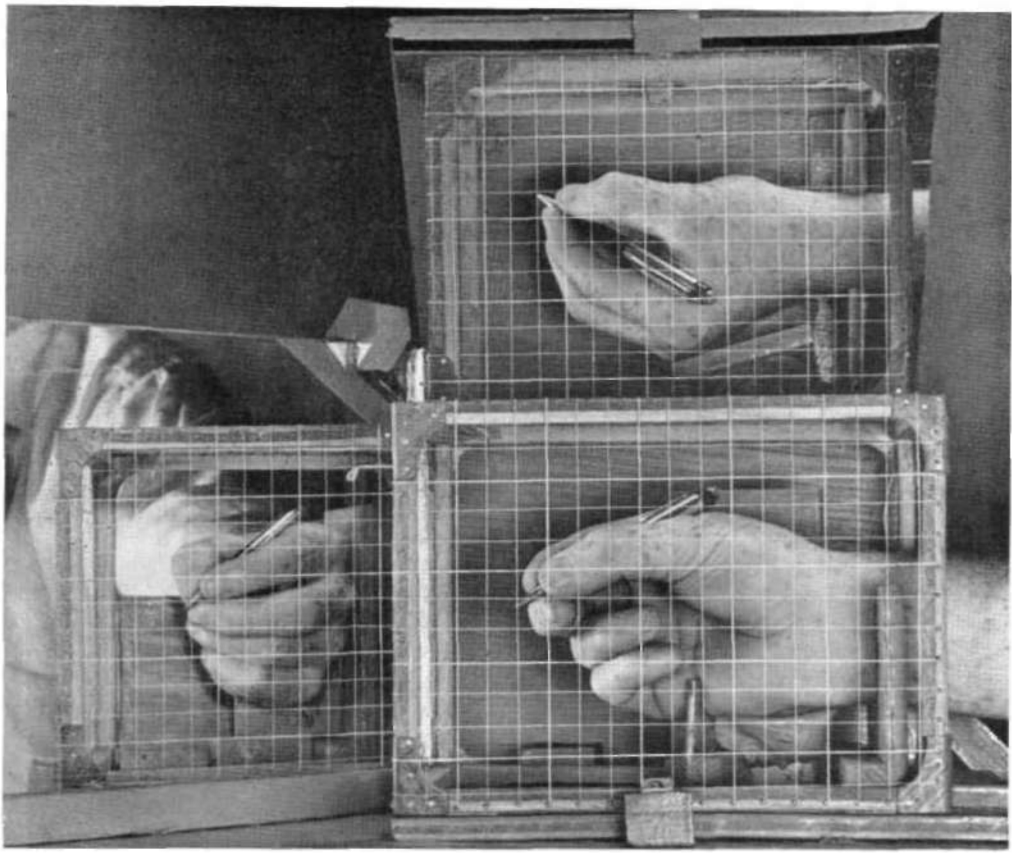

Fig. 8. Cage for observing hand prehension patterns in three dimensions simultaneously. The grasp shown is the typical palmar prehension of the three-jaw-chuck variety. *Courtesy University of California at Los Angeles.*

problem is to decide how these digits may best be activated.

Finger Design and Orientation

Aside from the problems of control introduced by fully articulated fingers, multisegmented artificial digits present problems of functional stability in use (Fig. 9). Because a finger comprises, in effect, a slender column, it presents a great lever disadvantage. To simulate each finger joint therefore introduces excessive lateral instability.

Fig. 9. One form of multisegmented artificial finger. Complexity such as this leads to lateral instability.

Moreover, it is difficult to design an operating mechanism that will fit within such a small space and that nevertheless will be rugged enough to withstand the stresses imposed upon the fingers. Careful selection of fixed knuckle angles, with articulation at the metacarpophalangeal joint only, lends greater strength, better lateral stability, and improved control of the prehensile pattern and confines bearings

Fig. 10. Artificial finger of monocoque construction with fixed knuckle angles so chosen as to cause grasped objects to be drawn into the hand rather than rejected.

and levers to the largest portion of the finger column (Fig. 10). The volar surfaces of the fingers and thumb should be padded to provide the prosthesis with a resilient and contour-conforming grip. Resilient pads afford the amputee additional surface-contact area and consequently increase the stability of grasp.

Thumb Design

Although in the normal hand the thumb is mobile, a feature which contributes greatly to hand versatility, it has been found that, in the artificial hand, which is lacking in sensation, a fixed-position thumb offers the best over-all advantage. A fixed thumb provides a registering point, an arrangement which lessens the possibility of accidental displacement of the object grasped, as is the case when both thumb and fingers move simultaneously and the amputee must guess the point of contact in motion. Moreover, a fixed thumb eliminates the necessity for complicated linkages between thumb and fingers.

It has been established through time-and-motion studies that a hand opening of approximately an inch and a half is adequate for 90 percent of all average activities, but an opening up to 3 in. is necessary for the remainder of the time. Since 1-1/2 in. of control-cable excursion is all that can be allotted for operating the terminal device, and since for maximum feedback of position sense a ratio of 1:1 between finger-tip travel and control-cable excursion is desirable, it is necessary to provide a mechanism that allows the thumb to be set at two positions relative to the hand itself in order to permit grasp of objects up to 3 in. in diameter.

A two-position thumb (Fig. 11) is made possible through the use of a unidirectional alternator mechanism which allows the thumb to be placed in either of the two positions by application of pressure on the dorsal side. When the thumb is in position to provide an opening of 1-1/2 in., pressure on the dorsal side releases the lock, and upon release of pressure the thumb is extended by spring force to an opening of 3 in. Application of pressure on the dorsal side a second time forces the thumb from the outer to the inner position where the lock engages

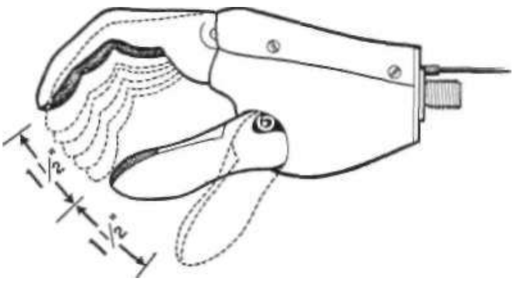

Fig. 11. The two-position thumb, set manually from either position to the other by application of pressure on the dorsal side. Inner position provides for objects up to *1-1/2* in. Outer position accommodates objects between 1-1/2 and 3 in.

automatically. When the lock engages, a slight, audible click indicates to the user that further pressure is not required. Such a thumb can be set by pressing it against some part of the body, a table, or the like, and thus does not require use of the other hand. With respect to the palm, the thumb should be located in such a way that, when the tips of the operating digits are touching each other, they fall in a plane forming an angle of 15 deg. with the longitudinal axis of the forearm (Fig. 12).

APPLICATION OF POWER

Currently the prosthetic fingers can be operated by one of two basic systems—voluntary-opening or voluntary-closing. In the voluntary-opening system, the amputee, using his motor control source, opens the fingers of the hand against the tension of a spring, and the spring, in turn, performs the clamping action in much the same manner as does a common spring clothespin. But the voluntary-opening device, although offering the advantage of simplicity, presents a number of disadvantages. It does not, for example, afford the amputee willful control over finger-tip pressure. Instead, the gripping forces are limited strictly to those provided by the spring tension, and the amputee must overcome a fixed, relatively heavy load each time the device is used. Since provision must be made to accommodate certain heavy tasks, the force needed to operate the voluntary-opening device is, for a large percentage of the time, much greater than is needed because the most

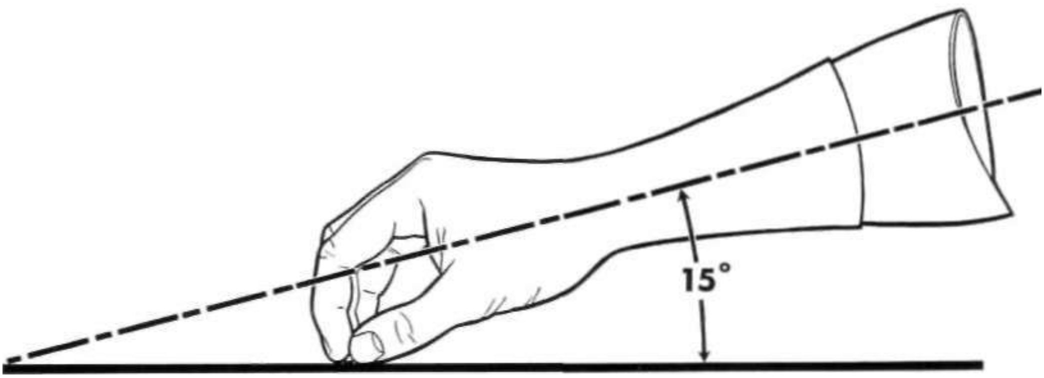

Fig. 12. Finger-thumb-palm orientation. The three-jaw-chuck pattern is so modified that the plane formed by digits I, II, and III forms an angle of 15 deg. with the axis of the forearm. Such an arrangement provides the most effective approach at table height.

frequent prehensions are in the light-grasp category (approximately 3 lb.). The amputee thus is subjected to excessive energy drain. Conversely, the voluntary-opening hand is unable to grasp delicate objects without crushing them. Besides all this, the motion required to operate the voluntary-opening hand is just the reverse of that in the normal, a needless complication.

In the voluntary-closing hand, the amputee, using his motor control, closes the device, and opening is effected by spring force. Because the voluntary-closing mechanism affords a natural pattern of motion and graduated, controlled finger-tip pressures, it offers the most likely possibility of duplicating the action of its normal counterpart. It can be used on delicate or fragile items and is capable of performing heavy tasks as well. Moreover, the force exerted by the amputee is related directly to the output forces desired. Forces equaling average natural prehension (18 lb.) are easily possible. Although the spring necessary to return the fingers to their open position and to withdraw the operating control to its starting position detracts from the over-all mechanical efficiency, if the spring is substantially linear in its characteristics it does not impair the amputee's ability to operate the device effectively.

With respect to grip, approach, and operating characteristics, the voluntary-closing hand performs efficiently. But unless a lock or clutch of some kind is incorporated, the hand would be carried in the open position, creating an awkward appearance, or else the amputee would have to exert continuous force on the control system to keep the hand closed. To overcome this problem, and also to relieve the amputee of expending energy for holding objects for relatively long periods of time, a lock or clutch appears indicated. To eliminate the necessity for using the other hand in engaging such a lock, an action which is not only inconvenient but which also often imparts awkward appearance, the locking operation must be independent. In the past, attempts to free the other hand from participation have involved use of a ratchet, but this expedient results in a limitation in the number of locking positions. The method which has given the most success to date is based upon a cam-and-quadrant system (Fig. 13). Relaxation of tension in the control cable from the energy source results in engagement of the cam regardless of the position of the fingers. Reapplication of tension in the cable dislodges the cam and frees the system.

It is important that the unlocking force be held rather high to eliminate inadvertent unlocking. A formula that has worked out rather well to date is that the unlocking force required should be about the same as that initially applied to the system when grasping an object and locking the mechanism.

Regardless of the method employed to

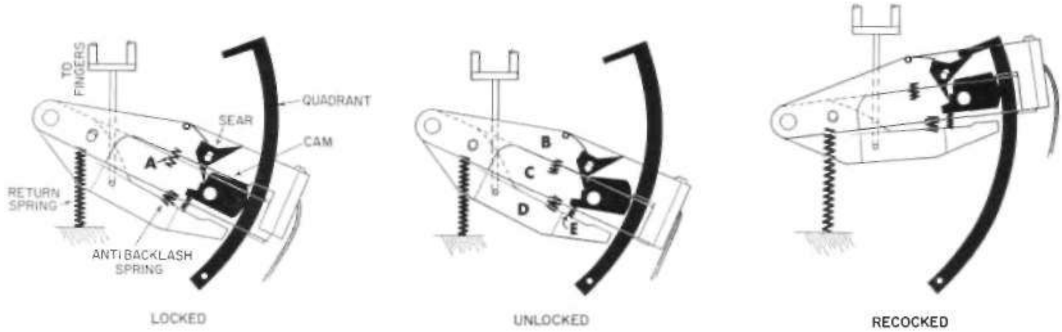

Fig. 13. The cam-quadrant clutch, schematic. The cycle is pull to close, release to lock, pull to unlock, release to open. In the locked position, compression force in return spring jams cam against quadrant to immobilize fingers. Small leaf spring maintains lower lip of sear in upper notch of cam but, owing to the separation of lever arms *B* and C due to compression spring *A*, *not* in such position as to rotate cam. Next pull on control cable closes lever arm *B* on lever arm C by compressing spring *A*, thereby causing sear to rotate cam counterclockwise against spring *E*. Mechanism thus is unlocked, and hand is free to open when tension in cable is released. Upon full opening, stop in fingers retains lever arm *B*, while stop on quadrant trips lower lip of sear into lower notch of cam to recock in preparation for next locking cycle. With next pull on control cable, cam idles along quadrant as fingers close, lower lip of sear remaining in lower notch of cam by virtue of slot in sear. When cable travel stops and tension is released, cam jams against quadrant again to lock, sear moves up on its slot to accommodate motion of cam, lever arm *B* is displaced from arm C by compression force in spring *A*, and lower Up of sear drops back into upper notch of cam in preparation for next unlock. Throughout the cycle, the compressed antibacklash spring tends to separate lever arms C and *D* and thus compensates for any slack induced in the course of the locking action. Since the quadrant is continuous, locking may be effected at any position whatever between full open and full closed.

achieve automatic operation of the lock, none can be successful unless some provision is made to eliminate the effect of backlash, an action inherent in all mechanical linkages. Unless backlash is eliminated, all or part of the prehension force is lost upon engagement of the lock, and no doubt several ingenious designs have failed to gain acceptance because this problem was overlooked or not solved.

THE REFLEX HAND

Although the voluntary-closing system probably represents the best available method for operation of an artificial hand, voluntary-closing should be viewed only as one stage in the development of a satisfactory hand substitute. One desirable addition to the voluntary-closing system would be to combine its advantages with those found in the voluntary-opening method. In the normal, for example, the hand usually is carried in a relaxed attitude. When it is brought to the zone of approach, it opens by visual cue to receive the object and then closes upon it. On relinquishing the grip, the hand drops back to its normal, or relaxed, position.

This "reflex" action can be duplicated mechanically and could be incorporated into a "reflex" hand (Fig. 14). At the first impression of force on the control cable the fingers open rapidly. When pull on the cable is continued, they close at the velocity of cable travel. The "push-pull" action is made possible by a lever system that presents a relatively high mechanical disadvantage when opening the fingers and then transfers to an advantage lever in the closing motion. Because of the transfer of lever characteristics, the system inherently provides a cue at full opening. Thus, one continuous motion of the control cable opens the fingers from the relaxed to the full-open position and then closes the fingers on the object approached. When the grip is relaxed, the fingers open to release the object and then return to the normal, relaxed position. Hence, the reflex hand would give the amputee all of the advantages of the voluntary-closing device and, at the same time, have some of the advantages

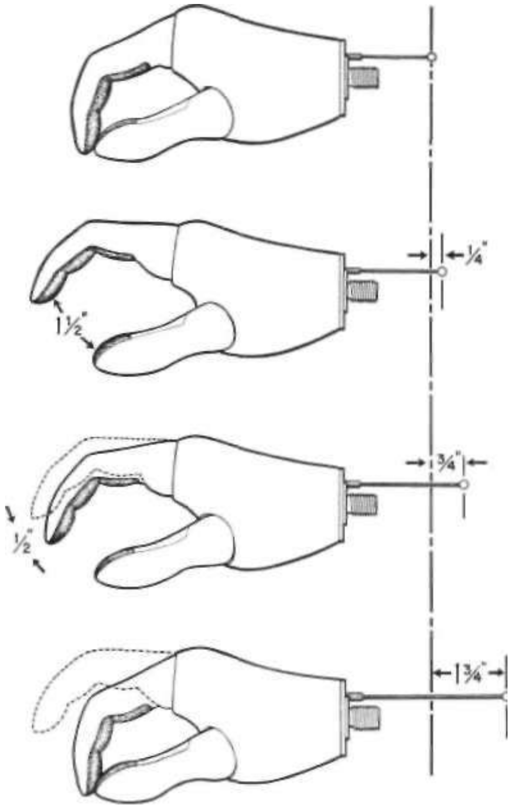

Fig. 14. The principle of the reflex hand. First 1/4 in. of excursion in the control cable opens the hand to the full 1-1/2 in. Further pull on the cable closes the hand at a 1:1 ratio of finger-tip travel to cable travel. Thus, after 1-3/4 in. of cable travel, the hand is fully closed again. The difference between the 1-3/4 in. total excursion and the ideal l-1/2 in. may be compensated for during the closing cycle by lineating mechanisms which give 1-1/4 in. actual cable travel. Upon release of tension on the cable, the action goes through the reverse cycle. The hand first opens fully (at a ratio of 1:1). Last 1/4 in. of cable excursion allows hand to return to closed or "rest" position. The excursion relationships suggested here are approximations; they may need minor modification on the basis of actual experience with test wearers.

inherent in the voluntary-opening device. Because of the "powered" opening *and* closing, it would also eliminate the major portion of the spring return, thus increasing the efficiency ratio of input to output force. In addition, powered opening furnishes a means of spreading pockets and the like to accommodate "blind grasp."

As in the voluntary-closing hand, a clutch is required to eliminate the need for the amputee to exert continuous pressure, and again it should be entirely automatic. If a one-motion cycle is to be achieved, the clutch must engage during the closing operation and then retain the maximum impressed grip force while the cable force is reduced. The average amputee can easily maintain 2 or 3 lb. of tension on the control cable. If, therefore, the clutch could retain the full grip of 15 to 30 lbs. of finger-tip pressure with, say, only a 2-lb. force on the cable, the amputee would not have to exert continuous maximum pressure. At this point some sensory cue must be provided to inform the wearer that further relaxation would release the clutch and return the fingers to their normal or starting position. Details of such a clutch design remain to be worked out.

To make the reflex mechanism versatile and adaptable, it should be a packaged, adjustable unit which, through its adjustment features, can be applied universally to all hands from the smallest to the largest. Standardization is perhaps the easiest feature to achieve because, if the clutching unit itself can be designed so that its case fits the smallest hand, adjustable lever shoes or arms can be attached externally to provide the greater lever advantage needed in larger hand sizes.

Other mechanical devices, currently available, can be used in the construction of an efficient reflex hand. Among them is a force multiplier that can be used to give the greatest impression of tip force at the time of contact with the object to be grasped. Also available are various lineating mechanisms that can be used to make the force response consistent over the entire range of finger motion.

THE FUTURE IN ARTIFICIAL HANDS

Successful transition from the natural hand to the prosthetic one depends in effect upon the judicious selection of the limited number of functions that can be replaced. The choice, in turn, depends upon three important considerations. First, it is necessary to determine those functions most essential to the activities of everyday living and of occupation in order to suit the mechanism to the operating requirements. Second, it is necessary to consider the practical possibilities of inanimate mechanisms and the details of stability, of friction, of linkage between components, and so on, to determine the characteristics of a feasible device within the bounds of cost, durability, ease of operation, and general ruggedness. Third, adaptation of the device to the amputee must take into account not only his functional needs but also to some extent his physiological and psychological characteristics. Such design problems in the matching of a mechanical device to the human being represent a particularly challenging example of biotechnology.

Because of the scarcity of available controls, present-day artificial hands are limited to a single pattern of prehension. Developments which would provide a second control, even of low power, would offer a great improvement, for example by adding an independent locking control. Such an eventuality would do away with the present disadvantage of the voluntary-closing hand, which now requires a second pull on the control cable to disengage the lock, followed by full opening to recock for the next locking cycle. Although the reflex mechanism described, which cycles first through an opening phase and then through a closing phase, would reduce and naturalize any movements required in preparation for locking, a second, and independent control source would represent a practical solution to problems associated with the existing voluntary-closing hand. Whatever the type of mechanism that finally emerges, the objectives are two in number. The first is concerned with preserving the graded prehension of the voluntary-closing device. The second relates to synchronizing the locking action so that, as in the normal hand, isometric grasp may be managed without additional time and motions beyond those made in the basic movements of prehension.

Other than the one additional independent control, no further motor functions are foreseen for mechanical hands any time in the near future. At some time more remote, hand prostheses may be powered externally by electric or hydraulic systems, but the inherent limitations of these power sources—the intricacy of structure, the difficulties in control and feedback, and the general complexity of operation and maintenance—make such developments long-range projects requiring much further study.

A major deficiency in all prosthetic equipment is the lack of any direct replacement of the sensory functions of the normal member. The natural hand, it has been noted, is richly supplied with sense organs mediating touch, pressure, and muscle and joint movement. It is therefore possible for the normal to recognize objects by shape, to sense magnitudes and directions of loading, to differentiate textures, and to perceive movements of objects, all via the intrinsic sensory mechanism. In the arm amputee, normal feedbacks from joints, muscles, and skin, stimulated by movement and pressure, are lost. In their place the amputee has only visual cues and the imperfect impressions from socket and harness pressures to aid in directing and operating the prosthesis.

Although visual control of a prosthesis can be shown in simple tests to be fully as precise as that in the natural hand, it obviously fails in the dark and, in any case, requires excessive concentration on the part of the amputee. Consequently, many aspects of manipulative function which are ordinarily habitual and subconscious become costly of time and visual attention when carried out with the prosthetic hand. Despite the possibilities of using substitute sensation from harness and control cable, many arm amputees never progress beyond the stage of simple visual control, and hence their concentration upon the task of operating the prosthesis introduces awkwardness in sharp contrast to the quasi-automatic operation of the natural extremity.

Fortunately, there is now a strong likelihood that feedback devices, signalling to proximal skin surfaces the extent of hand opening and prehension pressure by electronic, mechanical, hydraulic, or pneumatic means, will become a practical reality in the foreseeable future. Although there is still great need for extensive research and development in this field, satisfaction of the criteria for successful sensory replacement would constitute a significant advance in upper-extremity prosthetics and would give to the arm amputee greatly improved adeptness and sense of security.

Another area for research closely allied with the problem of sensory feedback is that of providing the "cosmetic" reflex movement in prehension and some realistic motion of the digits when the hand is idle, such as when it is carried empty at the side during walking. Experience to date with many arm amputees indicates that, were some slight movement of the fingers possible without too much conscious effort on the part of the wearer, perhaps merely through a coupling into a free-swinging elbow, the cosmetic effect would be enhanced appreciably. Still another area for improvement lies in providing a skeletal structure that will give a "live feel" more nearly like the anatomical counterpart.

Durability and ease of cleaning are, of course, important considerations in the choice or rejection of a cosmetic hand, but these problems would presumably be amenable to solution by the development of new and improved materials. Since in recent years technological advances, particularly in chemistry and in metallurgy, have provided a rapidly expanding list of materials with an ever wider range of physical properties, it seems reasonable to expect rather early improvements in the problems of hand maintenance, with respect both to the mechanical features of the hand itself and to its cosmetic covering.

Finally, it should be pointed out that the interpretation of research results and reduction of new ideas to practice both take time. Several years will be required before full utilization can be made of basic data already in existence. Meanwhile, further research and development proceeds apace. Perhaps, then, the most important requirements in the improvement of present hand substitutes are patience and perseverance on the part of all concerned.

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