

# Problems in Design of Artificial Hands

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Exact duplication of so intricate and efficient an organ as the human hand is, for all practical purposes, an impossibility. Lacking the power sources, nervous sensitivity, and automatic reflexes available in the normal hand, the designer is faced with the problem of providing a prosthesis that at least conforms to exterior configuration of the living counterpart. For many reasons, the replacement should present such a high degree of fidelity that it cannot be distinguished as an artificial device. But exterior reproduction limits the number and kinds of controls that can be incorporated into a fixed internal area.

The human hand is powered by some 24 separate muscle groups and is endowed with a cooperative pattern of sensitizing nerves. Motions in the normal are reflex or automatic, and very little conscious effort is required to manipulate the hand or fingers into a position of utility. In the amputee, however, such "mind-controlled" power sources and nerve supplies are not available to the designer. Although it is possible mechanically to provide substitute motions for almost all normal activities, lack of adequate control sources makes it impossible for the amputee to operate such device. It is necessary first to determine the optimum number and kinds of digital motions of the hand and what forces are required to operate the mechanism. It also is necessary to supply the prosthetic replacement with a motive source that is simple to operate and, at the same time, can provide the finger forces necessary for efficient prehension.

Scapular abduction provides a satisfactory major source of control, and it can be used to best advantage when there is some motivating stump remaining on the amputated side. In such a case, the opposite shoulder is used only as an anchor point. The forward thrust of the stump in the artificial arm provides the force and displacement required to activate the control mechanism that transmits operating forces to the fingers (9, 11).

All of these things considered, the designer of an artificial hand is restricted in the sense that he has at his disposal a limited source of power supply to operate any given device. Further, any hand prosthesis should be completely independent of the other hand, whether that hand be normal or artificial. In addition to these factors, the designer must consider the requirements of functionality and cosmetic appearance. Once the limitations and requirements involved are understood fully, it then becomes possible to outline some practical design criteria.

## DESIGN CRITERIA

### Finger Forces

For simplicity and ease of operation, input control to the hand should be a single control requiring but one cyclic motion. It therefore is necessary to determine the excursion possible, as well as the power or forces available to control the hand. This excursion-force or force-length curve should be worked out for what is considered to be a minimum and should be calculated to the strength available in the weakest amputee, but the hand

mechanism also must be stressed for the forces exerted by the strongest amputee. Thus, extensive force studies are needed in order to establish the maximum and minimum limits of motion and forces available (7, 9, 10) 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 1½ 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.

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 detailed studies of the uses of the human 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 all types of geometrical objects.

### Prehension Patterns

From fundamental time-and-motion studies, and through the transposition of certain habitual finger motions to another prehension pattern, it is found that the most effective, useful, and efficient grasp involves the action of the first and second fingers approaching and meeting the thumb at a converging angle (Figs. 1 and 2). The third and fourth fingers of the normal hand act as a resting shelf for holding a glass or other objects, as gliders when writing, and as reinforcing agents to the grasp. When their nerve sense has been removed, these fingers interfere with the normal approach of the first and second fingers. In the artificial hand, therefore, the third and fourth

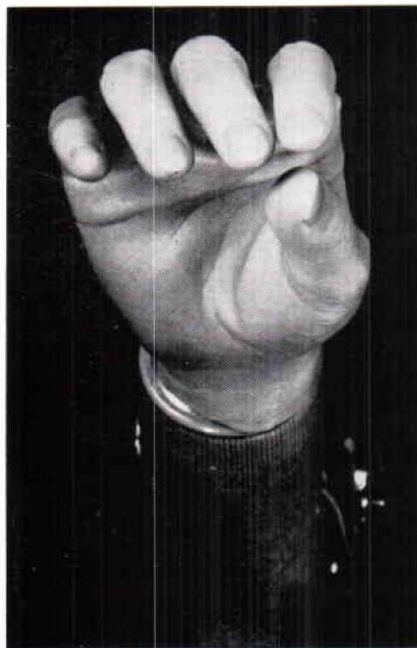


Fig. 1. The APRL voluntary-closing hand and cosmetic glove, showing the "three-jaw-chuck" prehension pattern. Courtesy Army Prosthetics Research Laboratory.

fingers are needed only for their cosmetic effect and should be designed to yield so as not to interfere with the approach of the "active" digits.

The output utility of the hand thus can be regarded as residing in the thumb and first and second fingers. The next problem is to determine how these digits may be activated to the best advantage.

### Design Tests

It is necessary first, through studies with normals, to list the most common and necessary manipulations of the hand. These functions include such things as opening various types of door locks, dialing telephones, using eating utensils, writing, combing the hair, dressing, carrying objects, and many other everyday functions. When the most practical pattern or patterns of prehension have been determined, the designer is faced with the task of producing an artificial



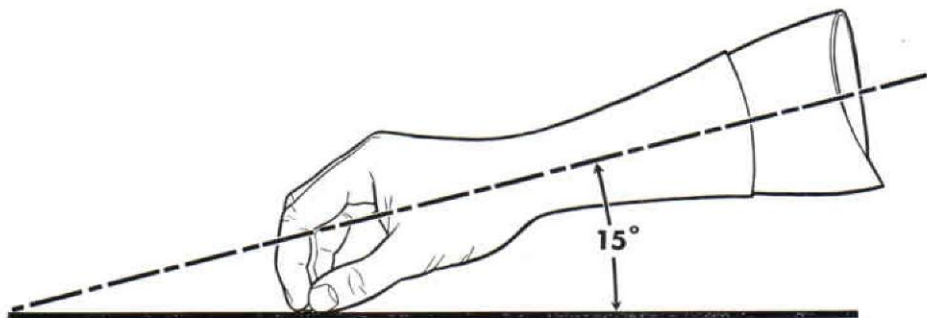


Fig. 2. Finger-thumb-palm orientation. The three-jaw-chuck pattern is so modified that the plane formed by the thumb and first and second fingers forms an angle of 15 deg. with the axis of the forearm. Such an arrangement provides the most effective approach at table height. Courtesy Artificial Limbs.

hand that embodies these basic characteristics. In order to evaluate the efficiency of design, an amputee equipped with such a prosthesis is given a test similar to the one used for normals.

Test results are discussed in the design conference, at which time hand structure, methods of conserving energy, and control movement are considered. Among the factors reviewed are the unit stresses on the hand and mechanism, exact attitudes of fixed phalangeal or knuckle angles for preventing ejection of the grasped object, finger position, stresses on operating links, cosmetic configuration of hand and cosmetic glove in all finger attitudes, and angle or plane of approach to an object. Other considerations include fixed angle of adduction and flexion, use of a fixed thumb as a registering point, resilience of the palmar surfaces of the fingers and thumb, locking characteristics for retention of grip without strain on the amputee, and minimum spring forces for returning the fingers to the open position and for retraction of the control cable or member through its housing or bearings.<sup>1</sup>

#### Hand Sizes

Considering the objective requirements already listed, the first important element of hand design is the establishment of hand sizes. Because the human hand varies greatly in size

and shape from person to person and even within the same person, it is necessary to construct an analytical curve based upon anthropological studies in order to determine, through experience, the sizes required to satisfy the amputee population (1, 2, 6, 8, 12).

No attempt is made here to enumerate all of the details involved in the design analysis needed to produce a satisfactory terminal device. Many factors, such as clothing, climate, industrial hazards, moisture absorption, exposure to salt water, toxicity, sensitivity, ease of maintenance, size-illusion factors, adaptability to changes, and psychological acceptance, require serious consideration.

It is agreed generally that five hand sizes provide a reasonable match for all amputees from the preschool child to the adult (Fig. 3). The five sizes permit manufacturers to provide a device at reasonable cost.

#### Models

Determination of the required dimensions is only one aspect 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 examined visually to compare subjective impressions. From experience with commercially available voluntary-closing hands and with experi-

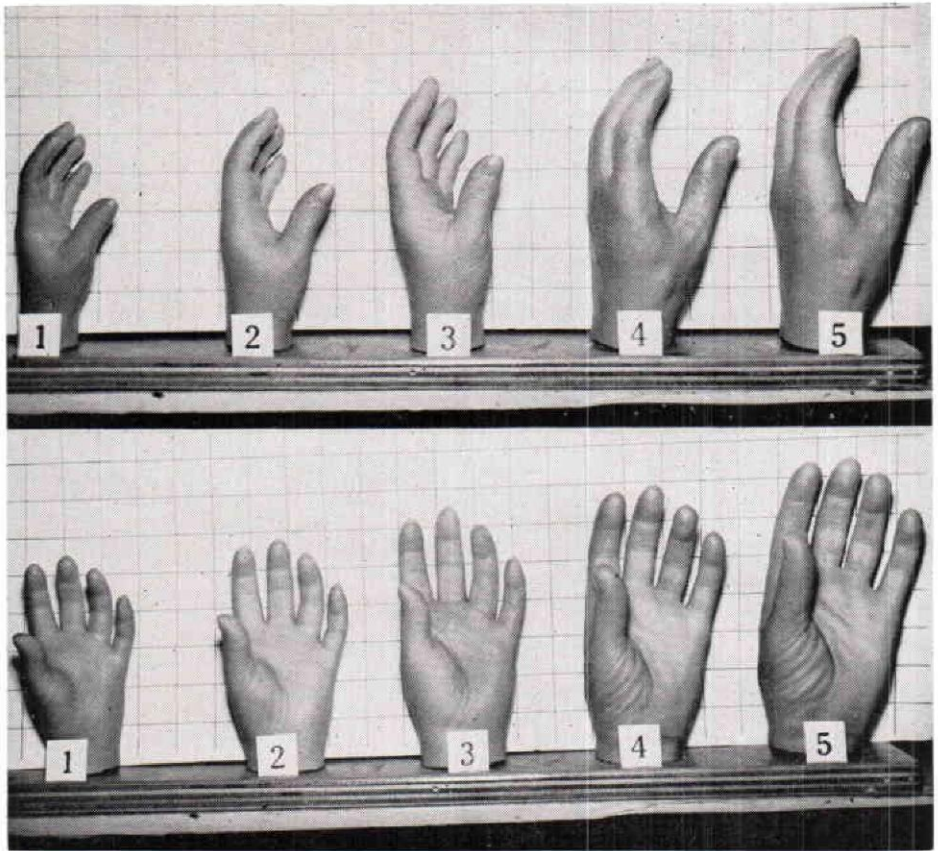


Fig. 3. Prototypes of the five hand sizes required to satisfy the population from age four to maturity. Courtesy Army Prosthetics Research Laboratory.

mental 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.

Because the specified dimensions 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. This simplifies considerably

the task of finding the model. Once a model is found to have the desired texture and approximate size, gross size changes can 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 were made for optical appraisal by a large group of experts in the prosthetics field.

Corrections then are made and electroformed molds of such hands are constructed and reduced by the thickness of the cosmetic glove. This process gives the exterior configuration and dimension available for the operating mechanism. The molds are then cut on pre-established lines,



again corrected for the mechanical considerations (by establishing pivot bosses for the mechanism, finger pivot bearings, stressing webs, and disconnects), assembled, tested for natural movement and coordination with a glove, and then 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 or skinlike glove, thus assuring gloves that fit precisely the finished hand mechanism.

### Finger Design

Because the fingers comprise the operating portion of the hand, their structure and method of operation are of extreme importance. At the outset, it would seem that the natural pattern should be followed in the articulation of artificial fingers, but the mechanical complexities of fully articulated prosthetic fingers must be weighed against their functional stability in use. Because the finger is, in effect, a slender column, it presents a great lever disadvantage. To imitate each finger joint introduces excessive lateral instability. In addition, it is difficult to design an operating mechanism that will fit into so small a space and, at the same time, that will be rugged enough to withstand the stresses normally imposed on the fingers. Careful control of fixed knuckle angles lends greater strength, better lateral stability, and improved control of the prehensile pattern and confines finger movement to the base or largest portion of the finger column or at most to one joint distal to the metacarpophalangeal articulation. The palmar surfaces of the fingers and thumb should be padded to provide a resilient and contour-conforming grip. Resilient pads afford the amputee additional surface-contact area and hence increase the stability of grasp.

Although the normal thumb is mobile, contributing greatly to the

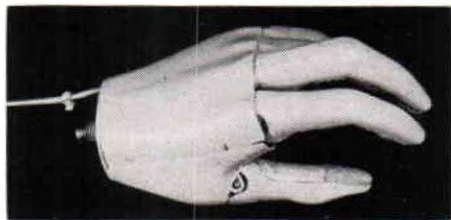


Fig. 4. The APRL No. 4C hand, now available commercially. The thumb assumes a fixed position, and the first and second fingers close upon it. The fourth and fifth digits are passive "floaters." Courtesy Army Prosthetics Research Laboratory.

versatility of the human hand, in the artificial hand a fixed-position thumb is most efficient (Fig. 4). It provides a registering point that prevents accidental displacement of an article, as is the case when the thumb also moves and the amputee must guess the point of contact in motion. Moreover, a fixed thumb permits the concentration of force in the first and second fingers, and it also eliminates complicated linkages between thumb and fingers.

### Two-Position Thumb

Time-and-motion studies have demonstrated that a hand opening of approximately an inch and a half is required for about 90 percent of all common activities (4, 5, 13). An opening of three inches suffices for the remaining 10 percent. Because  $1\frac{1}{2}$  inches of control-cable excursion is all that can be allotted to operate the device, and because a ratio of control-cable travel to fingertip travel of 1:1 is desirable, a mechanism is needed that allows the amputee to set the thumb in either of two positions in order to accommodate larger objects. The two-position thumb (Fig. 5) is made possible through the use of a unidirectional alternator mechanism that permits the thumb to spring open when pressure is exerted on the dorsal side. The thumb can be reset by the same pressure, the inner position being marked by an audible click or other sensory

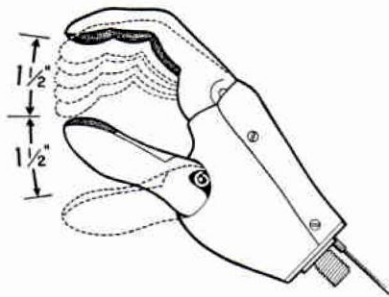


Fig. 5. The two-position thumb, set manually from either position to the other by application of pressure on the dorsal side. Inner position provides for objects up to 1 1/2 in. Outer position accommodates objects between 1 1/2 and 3 in. Courtesy Artificial Limbs.

cue. Such a thumb can be set by pressing it against some part of the body, a table, or the like, and does not require the use of the other hand.

## FINGER-OPERATION SYSTEMS

### Voluntary-Opening

Two methods of obtaining finger operation currently are available—voluntary-opening or voluntary-closing (3, 4, 5). In the voluntary-opening device, 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. Such a device is simple to design, and its application to different tasks is accomplished by varying spring tension or by using multiple springs. If such a spring-loaded system satisfied the criteria for a truly efficient prosthesis, the task of the designer would be comparatively simple.

But the voluntary-opening device has disadvantages. It does not, for example, afford the amputee willful, graded prehension or control of fingertip pressure. The forces possible in the voluntary-opening device are limited strictly by the available spring tension. Moreover, there is a definite limit to the maximum pressure attainable, and full force on the con-

trol cable is required to overcome the spring tension whether a light or a heavy grip is desired. If spring tension is increased to permit even medium-heavy tasks, the forces required to operate the device are excessive for the average amputee. Delicate objects cannot be handled, and the device is unstable because the fingers tend to relax when the control cable is placed under tension accidentally. Another disadvantage found in this type of hand is the unnatural motion required for operation. That is, tension is required to open the fingers and relaxation provides the clamping action, motions just the reverse of those used in normals.

The best that can be done with the voluntary-opening mechanism is either to make the spring loading continuously variable or to utilize several springs in parallel with provisions for selecting one, two, or more springs for varying the finger pressures. In spite of these disadvantages, however, the voluntary-opening device serves well for the most seriously handicapped, for those who desire limited function, and where economy and simplicity are valued above function and efficiency.

### Voluntary-Closing

In the voluntary-closing hand, the amputee, using his motor control, closes the device, and opening is effected by spring force. Hence, the prosthesis offers graduated, controlled fingertip pressures, a compatible or natural pattern of motion, and extreme stability of grasp. It can be used on the most delicate of fragile items and is capable of performing heavy tasks as well. At the same time, the force exerted by the amputee is related directly to the output forces desired.

In order to reverse the mechanical disadvantage of the fingers and to produce a 1:1 ratio of fingertip travel to input-control travel, thus obtaining a synchronous motion balance, such a hand should contain a force-trans-



fer mechanism, such as gears, cams, or levers. A spring must be used in this type of hand to return the fingers to their open position and to withdraw the operating control to its starting position. This feature detracts somewhat from the over-all mechanical efficiency of the device, but if the spring is substantially linear in its characteristics it does not impair the amputee's efficiency.

Insofar as grip, approach, and operating characteristics are concerned, the voluntary-closing device performs efficiently. But unless a lock or clutch is incorporated, the device would then be carried in the open position, and the amputee would have to exert continuous pressure on the control system to maintain grasp. These two factors would make the hand unsightly or unnatural in appearance and awkward to use.

To eliminate both of these drawbacks, a clutch or brake mechanism must be installed so that the hand can be carried in a natural attitude and so that the grip can be maintained without undue strain. Such a clutch must be devoid of backlash, automatic in its braking action, and releasable at the same control pressure at which it was locked. In other words, the clutch must lock at the amputee's will and at a force necessary to retain the object grasped and must release at the same control tension in order to maintain complete control of the object during the unlocking phase, all of which must be done with the one prehension control cable. The method which has given the most success to date is based upon a cam-and-quad-rant system. 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.

#### **The Reflex Hand**

Although the voluntary-closing system probably is the best method for operating an artificial hand, im-

provements could be effected by combining its advantages with those of the voluntary-opening system. The normal hand usually is carried in a relaxed attitude, but 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. 6). At the first impression of force on the control cable the fingers open rapidly and, by continuing the pull on the cable, close at the speed 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. Owing to the transfer of lever characteristics, this system inherently provides a cue on reaching full opening. Thus, one continuous motion of the control cable opens the fingers from a relaxed to a full-open position and 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 position.

The reflex hand would, therefore, give the amputee all of the advantages of the voluntary-closing device and, at the same time, have some of the advantages of 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 the reflex hand, as in the voluntary-closing one, a clutch is required to eliminate the need for continuous pressure, and it should be entirely automatic. If a one-motion cycle is to be attained, the clutch must engage during the closing operation and then retain the maximum impressed grip force while the cable force is reduced. It would not be too difficult a task

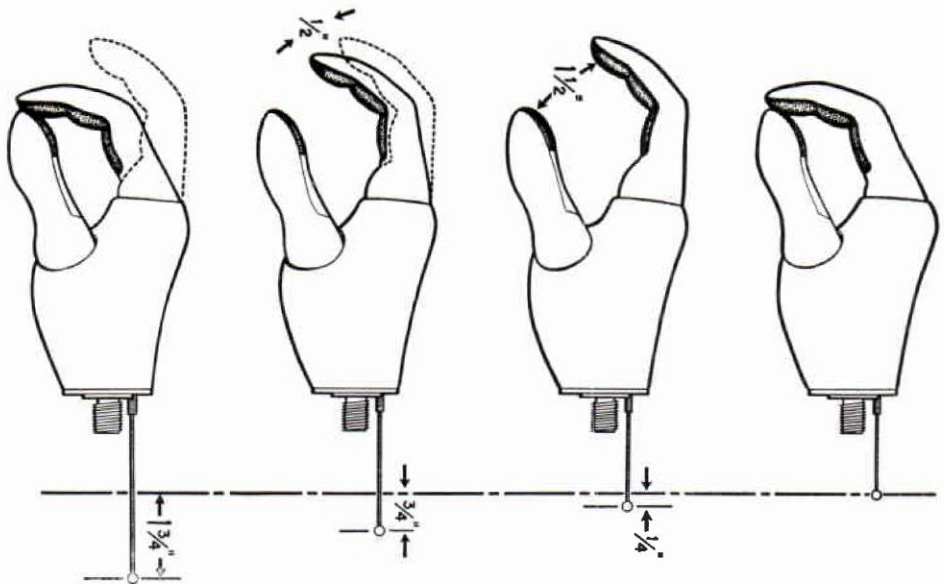


Fig. 6. The principle of the reflex hand. First  $\frac{1}{4}$  in. of excursion in the control cable opens the hand to the full  $\frac{1}{2}$  in. Further pull on the cable closes the hand at a 1:1 ratio of fingertip travel to cable travel. Thus, after  $\frac{1}{4}$  in. of cable travel, the hand is fully closed again. The difference between the  $\frac{1}{4}$  in. total excursion and the ideal  $\frac{1}{2}$  in. may be compensated for during the closing cycle by lineating mechanisms that give  $\frac{1}{4}$  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  $\frac{1}{4}$  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. Courtesy Artificial Limbs.

for the amputee to retain two or three pounds of tension on the control cable.

If, therefore, the clutch could retain the full grip of fifteen to thirty pounds of fingertip pressure, with only a two-pound force on the cable, the amputee would not have to exert maximum continuous pressure. At this point some sensory signal must be relayed to the amputee to warn him that further relaxation of control-cable force will release the object. Passing beyond this cue 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 used universally in 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 supply the greater lever advantage needed in larger hand sizes.

Other mechanisms available currently can be used in the construction of an efficient reflex hand. Among them is a force multiplier (Fig. 7) that can be used to give the greatest impression of tip force at the time of contact or impact 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.



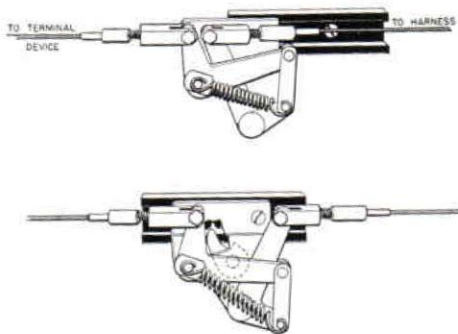


Fig. 7. One type of force multiplier. The tension in the coil spring is such that the spring is not overridden when there is applied to the control cable enough force to operate the fingers in the no-load condition. Thus, as long as the fingers are not in contact with an object, the ratio of cable travel on the harness side to that on the terminal-device side is 1:1, the lever arms maintaining their relative positions with respect to each other (top). When the finger tips meet a resistance of 3 lb., continued excursion of the control cable on the harness side locks the lever traverse to the base section of the multiplier, and force is then transmitted through the dual levers at a mechanical advantage to increase force at the fingers (bottom).

### THE FUTURE

In light of present knowledge of fundamental movements, grasp patterns, and sources of control now established as useful to the amputee, future research in terminal devices appears to be well defined. Of immediate consequence in design is the problem of sensory feedback. Needed in this area of study are definite cues that indicate fingertip pressures, finger openings, and the position of the hand in rotation. Such cues would be invaluable to the amputee, enabling him to achieve more casual and life-like movements.

Some devices have been tried with limited success, and others have been discarded. Among feedback mechanisms are the elementary devices consisting of tone-frequency electric buzzers and hydrostatic or hydraulic bladders feeding to a nerve center existing on the body. Direct-pressure

systems also are worthy of consideration as are the more complicated types of electronic mechanisms capable of picking up nerve impulses or of feeding electronic impulses into a sensitive area at various frequencies or concentrations. It also is possible to build into the harness and control system some of the basic cue mechanisms and, as illustrated by the change of mechanical forces in the reflex hand, some cues can be inherent in the device itself.

Another area of improvement is the skeletal structure of the hand under the cosmetic glove, the object being to give the device a "feel" comparable to that found in the normal. In light of structural requirements for hands, the need to replace or interchange cosmetic gloves easily, the space limitations within the handshells for the relatively complex mechanism, and the lack of suitable component materials for greater wear resistance having affinity for both metal and cosmetic gloves, this problem is not an elementary one. Rather, it is one requiring a great deal of development work and study. This phase of future investigation should, of course, be coordinated with the construction of an anatomical arm. Hence, it becomes an item of materials research.

Although the complexities of dexterous movement present in the normal hand never will be approached in a mass-produced mechanical structure, it is believed that a reasonable facsimile of the lost extremity eventually can be constructed. Such a device will return to the amputee at least the functional requirements necessary for holding his place in society in competition with normals without handicapping him, except in very narrow areas of employment where the hands are relied upon for their extreme dexterity and sense of feel. The highly sensitive nerve areas of the normal hand cannot be duplicated, nor can the complex manipulation of the hand be duplicated without requiring such a high degree of

concentration that the over-all efficiency is impaired seriously. Too, consideration of wear, abuse, maintenance, and the amputee's ability to operate effectively must always be foremost in the design of active replicas of the human hand.

Continuing research and development will lead to more sensitive, efficient, and natural-appearing artificial hands. But it must be stressed that the interpolations of studies and findings of the past decade will require additional time before they can be translated into sound, workable reproductions of the human hand.

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