MANIPULATORS AND UPPER-EXTREMITY PROSTHETICS

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After participating in the U.S. Atomic Energy Commission's Symposium on Manipulators, Project ROSE, Dr. Eugene F. Murphy, Chief, Research and Development Division, PSAS, got together with Dr. John Lyman, UCLA, and Mr. A. Bennett Wilson, NRC, for an informal chat on a number of ideas stimulated by the conference—some on historical developments and some on older concepts of prosthetics that might be applicable to today's manipulator problems.

The following notes are an outline of some of those thoughts, which, as Dr. Murphy described in a letter to Mr. Edwin G. Johnsen, Chief, Facilities Branch, Space Nuclear Propulsion Office, USAEC, "to some extent represent our joint thinking, but the wilder ideas should be regarded strictly as my own!"

We feel sure that for anyone who knows the ramifications of prosthetics research, Dr. Murphy's notes will sound more fascinating than wild. And for anyone who might ever have thought that research and development in prosthetics and sensory aids had limited applicability, these notes are a must!

The Editors

Motions and Gripping Requirements

In 1946–47, early in the government-sponsored Artificial Limb Program coordinated by the National Academy of Sciences, UCLA conducted extensive experiments on motions and gripping forces required for selected and common activities of everyday living. (These were deliberately selected as representative of independent living even for severely disabled bilateral amputees, though many of them were also difficult for unilateral amputees. Some were mutually exclusive, like holding a knife and holding a fork during cutting of meats, so that even a unilateral must perform either one or the other with a prosthesis. Industrial activities were *not* specifically studied, on the presumption that vocational guidance could locate suitable jobs among the tremendous variety requiring motions and forces no more severe than those required in everyday living and thus within the capacity of rehabilitated amputees.)

The typical gripping or pinching forces for a great many tasks were found to be 3 pounds or less at the finger tips, with only occasional tasks requiring as much as 6 pounds. The maximum pinching force encountered (pulling on shoes under certain conditions) was 14 pounds. Such high forces could be avoided fairly easily by use of a loop on the shoes, by further unlacing, or by wearing elasticized shoes. Independently, it was found that most amputees wearing voluntary-opening hooks closed by

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rubber bands typically wore only enough rubber bands to generate about 3 pounds pinching force at the hook tips with objects about ½ inch in thickness. Very few amputees, mostly bilateral, used as much as 6 pounds pinching force on at least one hook. Much higher forces *without* prehension could be exerted in lifting, pushing, pressing, etc., with the outer surfaces of the hook "fingers."

Accordingly, standards were set for terminal devices to pinch 3 to 3½ pounds readily but preferably to permit occasional development of 6 to 8 pounds. The Northrop-Sierra voluntary-opening hook closed by two coiled clock springs permits this choice by constant engagement of one spring but selective additional engagement of the second spring by moving a button on the operating lever. To engage or release the second spring, this button may be moved by bumping it against a fixed object in the environment or by using the opposite arm.

Prehension Patterns

The UCLA studies also explored the various finger motions used in a wide variety of activities of daily living. Probably the most frequently used form of prehension was the so-called "lateral," with the thumb engaging against the distal and intermediate segments and the intermediate knuckle of the index finger. This type of grip, very common in everyday activities, provides quite a stable grasp of objects with relatively flat sides. It is not, however, suitable for large objects, which tend to be expelled from the V-shaped notch between the thumb and index finger.

Larger objects are typically grasped by swinging the thumb away from the position of lateral prehension around toward the little finger so as to engage the tips of the index and middle fingers. Typically the index and middle fingers move inward on nonparallel planes so as to approach the thumb in a three-jaw chuck fashion.

Initially it was assumed that heavily curved fingers and thumb, all moving simultaneously, would be most versatile. Thereby large objects could be surrounded by the curved fingers and the flexed thumb in a fistlike grip, while small objects would be picked up by fingernails or mechanical equivalents. The concept of fist grip plus fingertip grip was later found to be a fallacy because the average objects of everyday living, such as knife, fork, pencil, etc., were engaged only in a unsteady grip on the small fingertips.

Later it was realized that a "flatter" grip would be more versatile for an artificial hand. In this so-called "palmar prehension," the fingers are less curved, the thumb is substantially straight, and larger fleshy pads engage at the fingertips. The APRL hand continues to be built in this fashion. This hand design is quite successful for unilateral amputees who are able to rely upon the remaining normal hand for very large objects, for delicate tasks, and for those requiring unusual hand shapes.

A fixed position of an artificial hand is imposed by the traditional requirement for a single operating control from a rather gross body motion, transmitted through a Bowden cable. Thus the artificial hand is unable to have the wide variety of finger shapes and types of prehension which are possible with the human hand with its multiple muscular controls.

Hook or Tong Design

The split mechanical hook, as a replacement for the artificial hand and an analog to the tongs used in manipulators, enjoys far greater versatility since it may be shaped deliberately to combine the various possible types of prehension of the human hand and yet operate from a single control source. In this sense, the hook may always be superior to the artificial hand at any given state of technology. The situation is somewhat analogous to the advantage of the airplane over the ornithopter; the airplane may take any arbitrary shape that is necessary to permit flight rather than being limited to a resemblance to a bird with its flapping wings.

Numerous types of artificial hooks have been used in this country and abroad for some generations. Originally the single question-mark-shaped hook, made notorious by the character Captain Hook in the play "Peter Pan," was widely used without any mechanical operation. Such a hook is useful for lifting, encircling and pulling, or pushing, but it is not useful for direct prehension. Some simple ring-type hooks have been widely used, particularly in Europe after World War I as a support for the handles of farm tools. Perhaps the most widely used hook in the United States has been the Dorrance-type split hook, available in a variety of patterns for specific tasks, and the somewhat similar split mechanical hooks developed by other manufacturers. One of the most widely used patterns is the Dorrance No. 5 split utility hook, formed of two question-mark-shaped "fingers" of somewhat different curvature. (These hooks were worn, for example, by Harold Russell in the film "The Best Years of Our Lives.") One curved finger is stationary. The movable hook (of somewhat different curvature in the portion near the axis) is integral with the operating lever. The latter, fastened roughly at right angles to the moving "finger" or hook, is attached to the operating cable from the harness.

The inner flexible cable of the Bowden cable, sliding through a housing anchored to the prosthesis above and below the elbow, passes across the back and is attached to a loop anchored to the opposite shoulder and passing through the arm pit. Forward motion of the upper arm (whether the stump of an above-elbow amputee or the complete upper arm of a below-elbow amputee) thus tightens this operating cable against its anchorage and relatively retracts the inner flexible cable, much as one's sleeve is drawn up the forearm by the forward motion of the arm, as in looking at a wrist watch. Relative retraction of the cable, with respect to the outer helically wound housing, then pulls on the operating lever and opens the moving hook fingers against the resistance of the rubber bands or metal clock springs which provide prehension forces. Relaxation of the shoulder in turn allows the elastic or spring to close the movable finger so as to grip an object between the movable and fixed fingers.

One of the features of the Dorrance No. 5 hook is the "canting" of the plane at which the "fingers" come into contact with respect to the axis of rotation of the movable finger. This canting, some 18 or 20 degrees, was considered desirable by Mr. Dorrance and seems to be appreciated by many amputees, though some other designers prefer a "parallel" design with plane of contact parallel to or containing the axis.

As part of the artificial limb program, in the late 1940's, UCLA and the Army Prosthetics Research Laboratory (now Army Medical Biomechanical Research Laboratory) collaborated in the study of hook finger shapes, based upon analyses of the UCLA motion studies and brief clinical trials of numerous experimental finger shapes at both laboratories. The result was the so-called "lyre" shape, by analogy to the musical instrument.

In the lyre design the plane of contact between the fixed and movable finger is parallel to and passes through the axis of motion of the movable finger. In the closed position both hook fingers are symmetrical about this plane. The portions of the hook fingers near the axis of motion, heavily curved in a plane perpendicular to the axis, were intended to allow the fingers to surround large cylinders such as drinking water glasses. Usually additional stability is provided by contact lower on the cylinder of the returning ends of the hook fingers, also curved in a plane containing the axis. The result should be contact with at least two (and usually three) points on each hook, making a total of four or six points on a uniform cylinder. Relatively irregular objects likewise are gripped at least at three points. The distal, heavily curved portions of the fingers meet in a flat portion which simulates the lateral prehension of the thumb against the side of the index finger for a great many common activities, notably with thin flat objects.

The inner portions of the hook fingers are rubber-lined to allow high coefficient of friction on most objects, but the external surfaces are deliberately made smooth to allow the hook to slip easily into a pocket or other close quarters. (Occasionally, for special tasks, an amputee has wished to return to the old practice of placing ordinary rubber tubing from a chemical laboratory over the entire hook finger, as had formerly been done with some of the conventional hooks. For example, one amputee who operated a sewing machine wished to be able to start the operating wheel by pushing with his hook! Such demands, however, have been rare, with most amputees preferring the smooth exterior finish yet high-friction inner lining.) The duckbill tip of each hook has a nearly semicircular metal rim to permit fine pincerlike prehension, and the outer portions of these tips are thinner than the main portions of the fingers to permit slipping through a button hole, for example, to grip the button.

As a result of the motion studies at UCLA, hook fingers of the lyre shape were designed to handle numerous objects of everyday life. These lyre-shaped fingers have been rather widely used in the Northrop-Sierra two-load voluntary-opening hook and on the APRL voluntary-closing hook, and somewhat similar hook fingers have also been adopted on certain models of the Dorrance hooks.

A basic premise of the Artificial Limb Program has been the use of one fixed hook finger plus one movable finger, in place of two symmetrically moving fingers. (A very few experimental hooks made with symmetrically moving fingers did not appear as practical in relatively informal clinical trials.) The concept has been that the amputee could use the fixed finger (or thumb), with the hook (or hand) open, as a guide to permit moving his entire arm to position the fixed finger against one side of the object to be grasped. He then might cause the moving finger to close, either by relaxing the operating control with a voluntary-opening hook or by causing voluntary prehension as with the APRL voluntary-closing device. This fixed finger as a guide for gross arm movements seems very practical, especially when dealing with relatively unstable or delicate objects. In contrast, for a symmetrically moving gripping device the estimated line of closure must be constantly centered upon the object to be gripped, a task presumably requiring much more delicate visual feedback. For a non-symmetrically moving device, the difficulties would be even greater.

Implications for Manipulators

It might well be that an analogous study of the *specific* tasks to be undertaken by each of specific categories of manipulators and other remote handling equipment could similarly lead to more versatile tongs and other special devices. The simple tongs, with dual flat opposing surfaces moving simultaneously, shown in numerous illustrations of manipulators, seem inherently limited in versatility and dexterity of prehension, in ability to lift loads without high gripping forces, and in contribution to positioning of the arm.

As Dr. Reswick suggested, the alternative possibility is to investigate changing of the task. In place of conventional but delicate laboratory glassware, he suggested more rugged materials might possibly be found.

Shapes, too, might be made more versatile. Ordinary devices, of course, are made with handles to suit the human hand; perhaps one needs "hookles" to suit mechanical hooks or "tongles" for manipulator tongs. In rehabilitation there is an analogy in the manner in which handles of everyday devices are modified with plastic materials to suit the limited ranges of motion and perhaps distorted finger positions of individuals with arthritis or other disabilities. A number of occupational therapists, in this country and abroad, have specialized in such adaptations as well as in the development of so-called technical aids such as long-handled combs, modified cooking utensils, and special clothing for the handicapped. The book, *Living with a Disability,* edited by Rusk and Taylor, and numerous publications of the Swedish Central Committee for the Care of Cripples (in Swedish SVCK), Ibsensgatan, Bromma, Sweden, for example, give a good deal of information on such adaptations and technical aids. Thoughtful analysis of those chemical laboratory tests, machine-assembly jobs, or other tasks performed by many manipulators might permit similar adaptations.

Prolonged Grip

It appears that force requirements with manipulators often include the necessity for prolonged holding of one object, such as a tool while it is being used, or perhaps acted upon by the opposite manipulator tong. It is our understanding that some individuals become fatigued by prolonged use of manipulators, even in handling relatively light loads. We understand that locking devices of some sort are available, sometimes operated by an electrical system through a push button. In some special forms of manipulators, we understand, it is possible to shift gears so as to obtain a higher prehension force at the expense of reduced excursion and speed. In most manipulators, though, according to one participant in the conference, a one-to-one force relationship is maintained between the finger grips at the master hand and the tongs on the slave arm, though the manipulator used by the opposite arm may occasionally be designed for a greater force ratio and correspondingly reduced excursion.

Wrist Position and the Blix Curve

It is well known that those muscles in the human forearm which cause most of the gripping action of the fingers have tendons which pass across the wrist joint; the tendons therefore are slackened by flexion or dropping of the wrist joint but stretched or tightened by hyperextension or cockup of the wrist. It has been known for many years that the force available from maximal tightening of a muscle at constant length, or isometric contraction against a rigid resistance, depends upon its length in relation to its so-called resting length. A Scandinavian physiologist, Blix, studied this problem many years ago with muscles isolated from the experimental animals and stimulated electrically. Maximal force is obtained at or just beyond the resting length, while the force of isometric contraction is reduced as the muscle is shortened. The force may be plotted for successive positions of shortening of the muscle. Eventually, at a little more than half the resting length of the muscle, the muscle becomes incapable of developing force when stimulated. This laboratory observation has practical applications. Children discover that they can make their playmates drop objects by pushing the wrist joint toward the flexed position so that the gripping force becomes minimal. Polio cases have often been fitted with a wrist cockup splint to allow maximum use of remaining feeble muscles.

This concept might be put to use by turning the tong of the slave arm in a master-slave manipulator toward the other arm to correspond to wrist flexion *without* requiring corresponding flexion of the gripping device on the master arm. Thus the operator might be able to have his hand in the slight wrist "cockup" or extended-wrist position at which maximum gripping force is obtained even though the tongs pointed somewhat toward each other, as is commonly needed for cooperative bilateral activities. It is our impression that this principle now is occasionally followed in master-slave manipulators, though most illustrations shown at the conference did not seem to illustrate variation from the exactly equivalent relationship between master and slave wrists which has always seemed desirable for sensory illusion. Perhaps only brief retaining of an operator, though, would restore the illusion that he was performing the task directly even though angular relations were altered.

Another, but more complex, method to obtain high gripping forces at any point necessary within a wide range of excursion might be the use of the voluntary-closing-and-locking mechanism used in the APRL hand and hook (with adaptations and proper materials, of course, for radioactive usages). In the APRL design, the necessity for an external, separate locking motion has been eliminated. Upon the first pull upon the single-control cable, the hook closes until it engages the object with any desired gripping force. When tension in the control cable is released, the hook remains locked upon the object with substantially the same force. (An antibacklash mechanism is used which could, in fact, be adjusted to give "front lash," even increasing gripping force, if that were desirable. The backlash typical of conventional *ratchet* locks, however, can readily be eliminated completely.) The object then remains locked with the original prehension force as long as desired.

When the operating cable is again tensed to a slightly greater force than was originally applied, the special APRL lock is released, but the object, of course, still remains gripped by this newly applied operating force. As the cable tension is again released, the object is released as the hook finger opens. If the hook finger is allowed to open completely, the lock is recocked ready for the next cycle. If, however, the hook is not allowed to go to its maximum opening, it remains ready for repeated voluntary closing and partial opening under control of the operating cable without operation of the lock; this feature is desirable for rapid manipulation in a so-called freewheeling mode which Colonel Fletcher aptly termed "applesorting."

In many operations of a manipulator, the "freewheeling" position might be quite adequate. The possibility of locking, however, might be desirable for prolonged usage to permit the operator to relax his forearm and intrinsic hand musculature. Unlike an amputee, the manipulator operator, of course, might be able to use his little finger to operate a push-button lock, but direct control might have some advantages.

Force Multipliers

A further possibility which might be considered is a so-called mechanical "force multiplier." This device was originally invented in Germany shortly after World War I for use with the skin-lined muscle tunnels created by the cineplasty operation, which in many cases of forearm tunnels did not develop very much force and excursion. The basic concept is to allow rapid motion of the hook tips (or finger tips) with respect to the operating cord, fanning air at a high mechanical disadvantage, until an object (of any arbitrary size within the range of the device) is gripped loosely. Then, when a predetermined resisting force is encountered (at any arbitrary position of the finger tips), the force multiplier locks and switches gears or leverages so that further motion of the operating cable (as by contraction of the muscle tunnel in cineplasty or the control cable of a conventional artificial arm) at a correspondingly high mechanical advantage rather than disadvantage applies very much larger force at the finger tips. Thus, assuming that the object is not very flexible, a large mechanical force is easily built up to grip the object. Presumably, such a mechanical force multiplier will tend to reduce sensory feedback, though the instant when leverages are altered could be made known to the operator so that he could estimate continued force increase. Several patents all available to the government, were taken out soon after World War II by participants in the Artificial Limb Research Program including Fletcher for a linear force multiplier, Conzelman, et al. for a linear multiplier, Motis for a force-multiplying hook, and Alderson for a rotary force multiplier intended for use with an electrical arm.

Because the average adult arm amputee can readily generate by proper harnessing adequate forces anywhere within an excursion of at least 1½ inches, force multipliers have never come into routine commercial use for artificial arms. The concept, however might be particularly suitable for master-slave manipulators intended to allow large gripping force on rigid materials yet large range of motion.

Selection of Desirable Motions

Motion studies at UCLA, described above, plus considerable discussion with amputees of their activities of daily life led to the concept of a relative priority for various types of motions in artificial arms.* Prehension is obviously very desirable. It is felt that an excursion of approximately 1½ to 1¾ inches would typically be adequate. The APRL hook could be adjusted to recock the locking mechanism at either approximately 1½ or 3 inches; it was presumed that in most activities of daily living the lesser motion would be adequate.

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*It might be worthwhile to talk with trained chemists who have become bilateral arm amputees.

(Because of the lyre-shaped hook it was possible to surround slightly larger cylinders such as water tumblers.) Voluntary elbow flexion was clearly essential. It is felt that wrist flexion, however, was of a lower priority but desirable, particularly for working close to the body. It is normally obtained by presetting a passive adjustment, perhaps capable of locking in only three positions; voluntary wrist flexion does not seem crucial. Radial and ulnar deviation, in a plane at right angles to wrist flexion, was considered to have a very low priority and has not normally been provided. Wrist rotation, equivalent to pronation and supination, is very desirable (though seldom available) as a voluntary control and is always provided, at least as a passively preset function. It can also be simulated voluntarily by shoulder abduction and adduction.

In contrast, manipulators have tried to provide full voluntary control of each of many independent motions. Possibly a hierarchy of motion priorities would be helpful.

Control Problems

Control of an artificial arm, like that of a manipulator, appears to be a combination of initial design and of training of the operator. (Amputees, unfortunately, are not susceptible to initial selection! Prescription of specific devices and training programs may help to meet the needs of individual amputees. To some extent manipulator operators can be selected. Even so, presumably it is desirable that any person who has occasion to operate a manipulator in conjunction with his other activities, such as chemistry, should be able to learn to do so.) Initial design of artificial limbs, like that of master-slave manipulators, has to a considerable extent emphasized direct similarity of motion. A study by Lyman and Groth, of UCLA, indicated that voluntary-opening terminal devices, closing and gripping by elastic means, permitted approximately as good sensory feedback as voluntary-closing devices. On an intuitive basis, voluntary closing seemed more "natural." (Some believe, however, that the voluntary-closing device tested, an APRL hook with its locking mechanism disengaged, suffered partially from the limitations of the very high return spring force which had originally been found necessary to pull the inner wire out of the Bowden cable housing to assure full opening of the hook and hence recocking of the locking mechanism.)

Earlier attempts to design an electrically driven type of auxiliary powered artificial arm emphasized the control problem. The amputee could *either* perform mental arithmetic or operate the arm in a complex task, but he was unable to perform both tasks simultaneously. Much of the work by Dr. Lyman's group at UCLA for a number of years has been devoted to study of the control problems for auxiliary power. In the case of artificial limbs or braces, control problems are made more complex by the inherent limitations of bilateral shoulder disarticulation cases, those with flail arms or the other most severely handicapped patients most needing auxiliary power. Presumably a manipulator operator, capable of moving his entire upper extremity in a complex series of independent activities, should be far less handicapped.

It is well known that tiny electrical activity occurs in nerves and somewhat larger voltages accompany muscular activity. Dr. Lyman's group has studied this latter electromyographic activity from a variety of the muscles in the upper arm and torso presumably most likely to remain available to a severely handicapped amputee. A considerable degree of independent on-off control can be learned fairly readily, particularly with the aid of electrical stimulation to emphasize the muscles to be used, but modulating control is very difficult to obtain. It is possible to develop some simple logic schemes to allow moderately complex decisions from only a very few independent on-off controls.

It is generally recognized that the skin is a high-resistance barrier over a highly conducting internal "salty sea" of body fluids in which the various muscles are acting, so pickup from skin electrodes is likely to be rather diffused and to involve considerable risk of "crosstalk."

Various concepts for using electromyographic signals for modulated and independent control, particularly based upon electrodes suitable for wear year after year, would appear some years in the future. While the problems of electromyographic pickup are considerably more difficult than is sometimes recognized, they probably are not insoluble. Surface electrodes are easily used for short-term measurements such as the taking of an electrocardiogram. The skin is sandpapered and a damp jelly is used between the skin and the electrode. Routine use of such methods for reducing the high skin resistance day after day for long periods would seem to imply dermatological problems. The dry silver-silver nitrate electrodes used recently for several days at a time on astronauts should be helpful.

Buried needle or wire electrodes likewise are very suitable for short experiments or clinical tests but do not yet appear practical for routine chronic use. Dr. Reswick's group at Case Institute and others have been considering possibilities of surgically implanted electrodes to pick up electromyographic signals and transmitters through the skin to permit better control and more precise localization of control signals than is possible with electrodes on the skin surface. It seems relatively unlikely that such systems, requiring surgical operations for implanting the devices, would be practical for most manipulator operators.

Electromyographic signal seems more promising than electroneurographic signal. One can pick up millivolts from the electromyographic signal compared to only microvolts directly from the nerve. One thus can think of the muscle as a sort of biological amplifier.

The possibility of external reflex arcs is still highly experimental but worthy of consideration. Professor Tomovic, of Yugoslavia, both in his native country and while he was at UCLA on a Ford Foundation Fellowship, has worked upon the possibility of a reflex hand. Dr. Hilde Groth, of UCLA, has gone to Yugoslavia to investigate his most recent designs and to run tests comparable to those already conducted at UCLA on other auxiliary powered devices.

Dr. Bottomley of St. Thomas' Hospital, London, also has developed an auxiliary powered below-elbow arm to test principles of external feedback loops of both force and velocity. This design is discussed in a recent article in *The New Scientist.*

Training

The importance of training of arm amputees has long been recognized. Much can be learned both from observing a skilled amputee such as Mr. Leavy but also from systematic training by a therapist who has given special attention to these problems. It might be possible to bring together some experienced manipulator operators and some occupational and physical therapists especially interested in problems of bilateral amputees. After some initial indoctrination, cross fertilization might prove useful.

APPENDIX I

Alderson, S. W., U.S. Patent 2,701,370, February 8, 1955, Prosthetic Device. [See especially Fig. 25 and Column 8, lines 3 to 35.]

Conzelman, Jr., J. E. *et al.,* U.S. Patent 2,582,234, January 15, 1952, Prosthetic Hand. [See especially Figs. 14 and 16.]

Fletcher, M. J., U.S. Patent 2,549,792, April 24, 1951, Control Device for Prosthetic Hands.

Motis, G. M., U.S. Patent 2,540,375, February 6, 1951, Artificial Arm Hook or Hand with Force Multiplier and Lock.

Klopsteg, Paul E., Philip D. Wilson, *et al.* Human Limbs and Their Substitutes, McGraw-Hill, New York, 1954.

American Academy of Orthopaedic Surgeons: Orthopaedic Appliances Atlas, Vol. 2, J. W. Edwards, Ann Arbor, Michigan, 1960.