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Dr. Boško ZOTOVIĆ

MEDICAL ASPECTS OF A HAND PROSTHESIS WITH AUTOMATIC CONTROL

I GENERAL

Substitution of a lost part of human body by suitable artificial means is one of the most serious problems in prosthetics. This problem becomes particularly serious when it is necessary to substitute the hand, this relatively small but very fine and complicated part of the human body. The designer of an artificial hand is immediately confronted with a series of difficulties which are sometimes impossible to solve completely. One of the basic difficulties lies in copying the unlimited possibilities of movement which the fingers and the hand possess, the volitional and unvolitional reflexes, the sensory and perceptive activities, the experiences which the hand acquires concerning the form, size, roughness or smoothness, weight and other qualities of an object. Further requirements which the designer has to satisfy in constructing an artificial hand concern the form, size and weight of the hand, its cosmetic properties power sources and the manipulating characteristics. Due to all these difficulties it is inevitable to resort to certain simplifications and neglect some less important elements. At the present stage and with the available means it is relatively easy to secure the basic crude functions of the artificial hand. There are also no difficulties in realizing a hand which completely satisfied cosmetic requirements but performs no functions at all. To realize an artificial hand, however, which will serve as substitute for the normal human hand both aesthetically and functionally, represents still a serious and most difficult task.

Due to the still unsolved problems of adequate constructive materials, appropriate power sources, limited space available for mounting the operating mechanisms, and inadequate form of the fingers, it is today possible either to satisfy aesthetic requirements by sacrificing functional properties or, conversely, to secure certain functional requirements on account of cosmetic properties. The most important defficiency of all the hand models known to-day is the sensory control of their functions. Our normal hand provides us with ample information concerning the form, size, consistence and other qualities of an object. It is able to apply adequate pressure to the object, to increase or decrease the pressure according to requirements, to adapt the position of fingers to the shape and the consistence of the object, etc. We are able to execute all these functions without having to see the object or use any other external assistance i.e. using exclusively our hand, experience and senses. Moreover, our normal hand is also able to adapt automatically its position in the space, which is very important for its normal functions. These are all properties which the artificial hands available up to now did not possess and which represented their most important defficiency. At the same time these unsolved problems provided the basic stimuli for our activities in this field. We hope that the automatic hand which is the subject of our paper will solve at least some of these problems and bring us nearer to the ultimate aim.

II - PSYCHOLOGICAL, FUNCTIONAL AND COSMETIC REQUIREMENTS

The basic guiding elements in designing an artificial substitute for a lost extremity are always of a psychological, functional and cosmetic nature.

As soon as a patient is fitted with a prosthesis he is confronted with a process of psychological adaptation to the prosthesis and particularly to an artificial hand. Adequacy of this adaptation depends largely on the patient's personal opinion about the extent to which the artificial hand corresponds to a normal one and where it differs most striking with the latter. This feeling is basic in accepting or rejecting the prosthesis on the part of the patient. It is known from literature that every person carries in his mind his body image. A lost part of the body, a lost arm or hand results in an altered image and a psychological effect on the patient. Artificial substitute which he obtains must satisfy the original image or to be as near to it as possible. This can be achieved only if the prosthesis meets both functional and consmetic requirements. In addition, it seems that the physical and social environment of the patient also plays an important rate, perhaps as important as the mechanical characteristics of the prosthesis.

Parallel with the psychological requirements are those of functional and cosmetic nature. As regards to functionality, the basic requirement the patient imposes is that his prosthesis, i.e. his artificial hand should operate in the same manner as the normal human hand. Another important element is the confidence which the patient acquires in such a hand by using it satisfactorily in various daily activities. It is of greatest importance that the patient be able to approach or attain such a level of automatic manipulation with the artificial hand where his activities with the hand become almost subconscious and require no major physical or mental concentration. If the artificial hand meets these requirements, we shall attain the aim of adapting patient's inner person to the artificial prosthetic means. In order to achieve this aim, the hand must be designed in such a way as to correspond to the normal hand in all respects. Naturally, we must not neglect the process of total rehabilitation of the patient, both physical and mental, to the prosthesis and its use.

Third important element is the cosmetic appearance of the artificial hand. As regards the cosmetic appearance, we shall only point out to the requirement of greatest possible resemblance between artificial and normal hand both in the form and size as well as other properties such as colour, presence of skin texture (hairiness, pores, blood irrigation), function and correlation between individual parts of the hand, the fingers and the thumb.

These are all elements which are always taken into account when designing an artificial hand. The problem, however, is how practically to realise such requirements. Artificial hands available until now did not succeed in fulfilling these requirements. Even in the most advanced form of APRL-hand, it was inevitable to sacrifice certain elements in order to incorporate others more importanc into the construction. The new model of the hand which is discussed in this paper, is much nearer to the final goal which we try to attain in constructing artificial hands.

III - A SURVEY OF EXISTING ACHIEVEMENTS IN CONSTRUCTING ARTIFICIAL HANDS

In this part of the paper we shall briefly refer to the existing forms of artificial hands and to summarize their basic characteristics. This will be done in order to facilitate understanding of the basic properties of our hand designed on the principles of automatic control and to enable evaluation of its advantages and disadvantages.

There are several existing models of artificial hands: Becker's type C, B and BX hand. Miracle type H-1, H-2 and M-1 mechanical hand, Robin aid mechanical hand, Peccorella's artificial hand, the very popular and the best available artificial hand - APRL. According to their properties, all these models can be divided into two basic groups: a) hands with voluntary opening and b) hands with voluntary closing. The common characteristic of all these models is that they enable only the basic movement to be performed such as "pinch" and palmar type of grasping. The main feature that distinguishes one model from the other is the action of fingers, In certain models only thumb is active, in others the thumb and the two first fingers, or all four fingers together while the thumb is passively moved to the desired position.

As regards the functionality, the APRL hand is most advanced. The first two fingers of this hand are functional, while the thumb is placed in the desired position with the aid of other hand. The superiority of the APRL hand over ofhter models consists in very close resemblance of its movements with those of the normal hand, in easy grasping of objects of various forms and dimensions and in the possibility of locking the position of fingers in an infinite number of arbitrary positions. With respect to size, this model is also superior to all others. Since the hand is regularly fitted with a suitable glove, the APHL hand satisfied the cosmetic requirements better than any other preceding model. The hand operates on the principle of voluntary closing, which also represents an advantage. A further advantage consists in the possibility of applying a pressure of 7-12 kgs. between the thumb and the forefinger, which is not possible with other models.

Despite all these advantages, the existing models of artificial hands have many defficiencies which are mainly of a functional nature and to a less extent of cosmetic nature. The basic defficiency is the very limited excursion of movements which they can produce and the insufficienc resemblance of these movements to those of the normal hand. This is reflected in the fact that, when grasping an object, only two fingers are actively engaged while all others remain passive and the thumb must be brought to the desired position with the aid of the other hand. A further defficiency consists in the use of a system of cables and harness to activate the hand, which means that the intervention of the shoulder joint is necessary for opening and closing the hand unlike normal hand operation where the shoulder joint takes no part. Visual intellectual and sensory effects accompanying the operation of such a hand are far from being identical to the effects accompanying the action of a normal hand. Their mutual relation and importance are also different.

Due to all these defficiencies the existing types of artificial hands cannot represent an adequate substitute for the normal human hand. This in fact is the main reason why constant efforts are invested in this field in order to come as close as possible to the final aim. In the text that follows we shall try to present the basic principles underlying the automatic hand and to point out to those elements which we consider to be new and positive and which make this hand superior to all those that have been mentioned previously and that are commercially available.

IV. THE AUTOMATIC HAND

It may be interesting to explain at the very beginning why this artificial hand can be considered to approach the normal human hand to a greater extent than any of those that are commercially available. Let us remember that the normal human hand is activated through 24 muscular groups whose action is very closely coordinated and controlled by a network of nerves directly connected with the functions of the brain. Since the movement of our hand are of automatic and reflex nature, it is necessary to invest very little conscious control in executing a movement such as e.g. grasping a glass or a similar object. The positioning of fingers and the pressure they exert on the object is controlled by normal peripheral sensations which prevent the breaking of the glass.

Looking at the performance of our automatic hand, we see that it operates in almost exactly the same manner. It enables all movements to be performed automatically in a way that is similar to the operations of normal hand. The afferent sensations produced in normal human hand are substituted by special artificial sensations which shall be discussed later and which determine the amount of pressure to be applied to the object grasped by the hand.

Size and form

As regards the form, our basic aim was to achieve greatest possible resemblance with the normal human hand. Space requirements for the operating mechanism were not very serious so that the thickness of the hand is within the limits of the normal hand. The basic dimensions which were taken into account are: a) width of the hand measured from the radial part of the head of the second metacarpal bone to the ulnar part of the head of the fifth metacarpal bone; b) dorsal length measured from the centre of the proximal part of Os Lunatum to the tip of the metacarpophalangeal joint of the third finger; c) length of the middle finger taken from the metacarpophalangeal joint to the tip of the finger and d) thickness of the palm represented by its lateral dimension.

As regards the size, in the first stage of our research we have taken into account only the size of an average man's hand. In our future work we shall take into consideration four additional sizes to cover all age-groups for both sexes starting from the age of four. In this work we shall use the well-known results attained at the University of California. In determining the size of the hand we shall also take into account thickness of the rubber glove.

Walls of the hand shell

A closely related problem with the size and the form of the hand is the thickness of the material to be used in constructing the fingers and the palm. While this thickness should be as small as possible, it is necessary to secure a sufficiently resistan wall to counteract cyclical forces that may be produced during activation of the hand. Of particular importance is the thickness of walls of the phalanges which are of the same number as in the normal hand. Excessively thin walls of the phalanges may result in medio-lateral instability in the inter-phalangeal joints and partly neutralize the functions of the hand. In order to satisfy these requirements we shall use a special magnesium-aluminium alloy of a thickness of less than 0.9 cm (0.0875 cm).

Since the hand will be covered with a cosmetic glove, the total wallthickness will be slightly increased. The properties of the glove will correspond to those of the normal human skin and will be made along the same lines as the cosmetic glove used for the APRL hand. It is interesting to note that some experiments which we made with the existing cosmetic gloves showed that the action of our automatic hand was considerably neutralized by the thickness of these gloves. For these reasons the cosmetic glove to be used with our hand must be somewhat thinner and more elastic than the existing ones. These gloves will be made of plastic polivynil chloride and produced in sizes corresponding to the sizes of the hand.

Range of motion of the thumb and fingerjoints

As mentioned previously, the hand is characterized by mobility of all fingers and the thumb. The fingers and the thumb correspond to those of the normal human hand not only in form and size but also in configuration. The thumb has two phalanges and the remaining four fingers three phalanges, i.e. the hand possesses functional metacarpophalangeal and inter-phalangeal joints. The degree of movement allowed for each of these joints is based upon the works of brothers Weber and Fischer. For the flexion-extension of metacarpophalangeal joints of fingers we allowed 90-110° and for flexion-extension of the thumb 50-70° (extention is negligible). Extension in the metacarpophalangeal joints, which normally amounts to 15-20° with respect to the neutral plane and which represents actually a hyper-extension has not been taken in account since this movement is rarely used, particularly not in artificial hands. As regards the inter-phalangeal joints of fingers the degree of flexion of proximal joints is 70-130° and that of distal joints 60-70°. Flexion of the inter-phalangeal thumb joint is 60°.

There were several reasons that led us to adopt a range of 20-30° in determining the mobility of certain joints. One of these reasons is that the differences encountered between one human hand and another fall within this same range. The same applied to the differences that exist in the degree of mobility of joints among representatives of different races and the influence of environmental and living conditions on the development and function of certain parts of the body and joints. Another reason was the friction resulting from the functioning of the artificial metacarpophalangeal and inter-phalangeal joints of the hand which reduces to a certain extent the mobility of these joints. This range was further dictated by the limitations in the quality of material used for the construction of the driving mechanism, such as coefficient of friction, thickness, etc., as well as by the system of levers used for activating the hand. These are all elements that may affect the degree of mobility.

The function of the wrist, i.e. dorsal and plantar flexion, radial and ulnar deviations, has not been taken into consideration. The main reason was the complexity of the hand construction and the fact that these movements were not considered to be essential for the function of the hand. This defficiency in the function of the hand is compensated by positioning the hand with respect to the plane of action in such a way that the finger axis makes an angle of 15° with the base. This is a well established method of positioning the hand used both by upper extremity amputees and by normal persons. The lack of rotational movement of the wrist is partly compensated by choosing a proper socket for the prosthesis. We shall come back to this point later on.

Operating mechanism of the fingers and the thumb

The fingers function in the following way: when the fingertips approach a certain object a slight flexion of distal phalanges is first initiated, then follows the flexion of proximal phalanges and finally the flexion in the metacarpophalangeal joints. The mutual relation of the degree of flexion is adjusted in such a way as to correspond as adequately as possible to the functional requirements of the patient and to the function of the normal hand. Flexion of the metacarpophalangeal joints is slightly delayed with respect to the initial flexion of the distal inter-phalangeal joints. This is of particular importance for enabling cylindrical grasping, as well as grasping with fingers in hook position. This delay is further useful when it is necessary to clench the hand, because a much greater amount of movement in the inter-phalangeal joints can be accomplished simultaneously with the full amount of movement in the metacarpophalangeal joints so that the fist can be formed in a proper manner.

Unlike the other models of artificial hands, the thumb in our model is also active. To enable proper function of the thumb, the thumb is slightly rotated with respect to other fingers and the plane of its position makes an angle of about 45° with the plane of position of other fingers. In this way, semi-oposition of the thumb is also made possible to serve in proper formation of the fist. Thanks to the rotated position of the thumb and the adequate flexion of the metacarpophalangeal and interphalangeal joint, the thumb can be used for a very broad range of activities.

The interaction of the thumb with other fingers is arranged in a sequential manner so that first the fingers assume a preparatory position for a given type of grasping and then follows the preparation and flexion of the thumb. The different forms of these functions will be described later.

Problems of power sources and control

Description of the mechanical design aspects of the hand are treated in a separate paper. We shall deal here only with medical aspects of the problem. As mentioned earlier, all artificial hands belong either to the group with voluntary opening or to the group with voluntary closing. Our hand designed on the principle of automatic control belongs to the group with voluntary opening.

Closing of the hand, i.e. its flexion in certain or all joints, as accomplished through sensory cushions located in the tips of the fingers and the thumb, and in the palm. Thanks to these sensory elements, made of particles of microphone dust, this hand is able to close, to take or grasp an object. Depending on the shape of the object, its weight, roughness or smoothness, the applied pressure will vary. One of the still unsolved problems is the inadequacy of this pressure which is considerably less than the pressure available with the APRL hand. In the first stage however, we did not place emphasis on this problem and its solution has been postponed for a later phase of research.

Another point which should be mentioned in this connection, is the fact that the fingers adjust themselves automatically to the shape of the object, thanks to a certain amount of flexibility and the positive feedback which enables close and firm holding of the object. No breaking mechanism is required, since the hand will lock itself automatically in the required position thanks to the positive feedback.

The control of such actions is made possible by means of standard servomotors and there is no need for conscious control or for the use of muscular energy. All signals initiated on the periphery are transformed into electricity and, due to the closed current circuit, the fingers and the hand remain practically in a locked position which can be maintained without any energy being required from the patien as long as this current circuit is not broken willingly.

The method of breaking this current circuit and the voluntary opening of the hand i.e. extension of the fingers, represents a problem of special interest. Instead of inserting a number of switches to break this circuit with the aid of the other hand, or leaning the prosthesis against a hard object, we have inserted sensory elements in certain parts of the stump. Locations which are considered to be suitable are the region of olecranon and the region of biceps. In this connection we should point out that when fitting this hand in cases of forearm amputations we intend to use exclusively preflexed forearm prosthesis supported by olecranon and suspended by means of a biceps cuff.

By inserting corresponding sensory elements in these locations, the patient is enabled, by extending the stump which is always in a preflexed position, to exert sufficient pressure on the sensory cushion of the olecranon and break the current circuit. This will result in the extension of fingers i.e. in the opening of the hand. If this extended position of the stump is impractical for opening of the hand, as may be the case when it is necessary to open the hand with bent elbow, we shall use the contraction of the biceps to exert pressure on the sensory cushion located in the biceps cuff and enable the opening of the hand in such a position. In this way voluntary opening of the hand will be possible in all position of the hand, either extended or flexed.

A separate problem is the method of increasing the pressure while holding an object in the hand. This problem is still in the process of study and experimentation. One of the spots which can be used for this purpose is the bottom of the prosthetic socket or the lateral side of the stump. At this moment it is difficult to say whether these spots are the most suitable or some other will have to be taken into consideration. It is however at once obvious even now that this problem will have to be solved in the next stage. The solution will be found after extensive experimentation with patients.

It would be of interest to investigate in this connection whether there exist any possibility of establishing connection between the pressure of fingers while holding an object and the opening pressure through the olecranon or biceps and in this way to accomplish exactly what is being done under normal conditions both by gonistic and antigonistic muscles when initiating a motion and adjusting the pressure. Let us also mention that when at rest the automatic hand is in a semi-open, neutral position which closely resembles the free position of the normal hand when at rest,

Functions of the hand

Normal human hand is able to execute an infinite number of diverse actions. Certain movements are rarely encountered in everyday life and are associated exclusively with certain specific vocations. Such movement will be very difficult to perform for all those who are not used to this vocations and would require special training. It is obvious that such fine and rare movements cannot be taken into consideration for an artificial hand. What we are interested in are the functional abilities of the artificial hand with respect to elementary and everyday movements. Such movements are limited in number and, in order to simplify the discussion of the hand functions, we shall deal only with the basic types of prehension of which there are only 6 to 7. These are: cylindrical grasping, grasping with fingertips, grasping with fingers forming a hook or gnap, palmar, spherical and lateral type of prehension.

If we analyze the abilities of all the artificial hands produced until now, we shall see that very few of them can perform more than 2 or 3 types of the above mentioned elementary movements. In this respect, the automatic hand is considerably superior. It is able to perform all these movements except lateral grasping, which is rarely used even in normal human hand. Spherical grasping, a movement which was impossible to accomplish with artificial hands, has now been made possible for the first time with this automatic hand. The position of the fingers and the thumb is adjusted to the roundness of the object in a fashion which completely immitates the normal human hand. A further functional defficiency of the older models is the passive position of the fourth and the fifth finger, whereby certain actions are hindered. This defficiency has now been eliminated for the first time with the automatic hand. As an example we shall take the holding of a pencil. To hold the pencil in an artificial hand a good amount of skill is necessary as well as specific positioning of the hand which is far from resembling that of a normal hand. With the new automatic hand the pencil is held by palmar type of grasping, where the fourth and the fifth finger, following the flexion of the thumn and the first three fingers, are flexed almost to the maximal position permitting thus not only easy and correct function but also normal position of all fingers of the hand.

These few examples are sufficient to show that functionally this hand is superior to other existing models. This may even justify the assumption that this hand will be able to perform many other actions which do not fall within this elementary group of six or seven basic movements. If this turns to be true, we can expect that patients with amputated upper extremities will be more easily rehabilitated with such a hand and brought back to their original profession without need for requalification for a job placement or a new job. Herein lies the basic importance of this hand which makes possible the rehabilitation of patients not only in the sense of ability for work but also in the psychological, physical and cosmetic sense.

Socket of the prosthesis and means of suspension

Our presentation will be incomplete unless we refer briefly to the form of the socket and the type of suspension. In this first stage of work on the automatic hand only forearm amputations had been taken into consideration. We shall therefore limit ourselves to the sockets and suspensions concerned with forearms. It is necessary to devote some space to these parts of the prosthesis, since they represent an integral part and contribute to a certain extent to the functions of the artificial hand. The socket for the forearm prosthesis is manufactured by using the technique of dr. Kuhn, It represents actually a plastic preflexed forearm prosthesis supported by the olecranon. The socket has a double wall, the outter one serving as a shell for connection with the hand and for eventual mounting of the hand mechanism. The inner wall represents the actual total contact socket. It is important to stress this because total contact enables better stability of the stump in the proshtesis and simultaneously permits the use of afferent nervous sensations on the peripehry of the stump. This compensates partly the lack of sensations from the hand itself and facilitates the positioning of the prosthesis and the hand. In this way we come much closer to the basic visual, intelectual and sensory requirements regarding the action of the prosthesis and the artificial hand.

The lack of rotational movement of the wrist was already mentioned as a defficiency. This defficiency is, however, partly compensated by a screw driver type of socket which permits pronation and supination. In the older tpyes of sockets these movements were practically lost. In this way the absence of wrist function in the artificial hand has been compensated in a fairly adequate way.

We should mention another element of the socket which is important for the function of the hand. This is the sensory pad which, when pressed by olecranon, enables voluntary opening of the hand, i.e. extension of the fingers. This was already discussed earlier.

Suspension consists of the biceps cuff and two leather straps which connect the cuff with the prosthesis. Harnessing is not used at all. From the aspect of automatic control the biceps cuff is important because its front part is fitted with a sensory pad serving as the second zone for voluntary opening of the hand, which can be effected by volitional contraction of the biceps muscle.

Let us finally stress that the fore-arm prosthesis is very light and that, taken together with the weight of the hand, it does not represent any serious load to be lifted to a definite height. This means that the prosthesis satisfied the principle of lever action where the active parts - muscles and the length of the stumps - are always adequate to raise the lever to the desired position.

In this way the elements which were not solved by the hand itself have been compensated by the socket, improving thereby the functions of the hand and adding nothing to its size, weight, or complexity. In solving these problems we have not departed from the basic rules of kinaesiology and biomechanics which apply to the normal human arm and hand.

Indications

In this stage of our work we have concentrated all our activities to fore-arm amputations. It is important to note that the prosthesis can be used for all levels of amputation and all forms of the stump, including desarticulation of the wrist. In this latter case the entire operating mechanism is mounted in the wrist. It should be stressed, however, that in this case the prosthetic side is somewhat longer than the sound one, but the difference is so small that it does not affect the simmetry of the body and the cosmetic appearance of the patient.

There exists also a realistic possibility of using this hand in the cases of desarticulated elbow and upper arm amputations. It would be necessary, however, to select appropriate locations for the sensory elements which would enable voluntary opening of the hand, by using normal physiological movements. It is obvious that in such cases it is necessary to use figure eight harness but their function would be exclusively to suspend the prosthesis. Even in these cases it would be possible to perform different actions similar to those in the case of forearm amputations and to include visual, intelectual and sensory elements to make the action of the hand and the prosthesis more physiological.