Orthotics and Prosthetics, Vol. 35, No. 1, pp. 1-6, March 1981

A TERMINAL QUESTION

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Terminal devices for upper-limb prostheses, mechanically operated "hooks", have remained basically unchanged for more than 25 years. This lack of innovation has severely limited the options available to upper-limb amputees when seeking a terminal device suited to their particular set of needs. Up to now, the choice available to upper-limb amputees has been primarily variations of the voluntary-opening split-hook. This particular design, and its variations, has been prescribed often in an effort to meet all of the needs of the majority of upper-limb amputees, regardless of the level of the amputation.

Even the most superficial examination reveals how inadequate these prescriptions have met the needs of the patient. The more popular model of hooks provides the pinching action analogous to that of forceps, and the gripping strength is limited to the power provided by rubber bands or springs (approximately four lbs per rubber band). The currently available voluntary opening hooks have performed admirably in light duty applications for bilateral amputees, but, have proven less than adequate when used for vigorous activities, since tools and other objects tend to be forced out when pressure on the hook fingers exceeds the rather limited capacity of the rubber bands. Perhaps a voluntary-closing device might be better suited to the demands of strenuous work and recreational activities.

In spite of the fact that some rather sophisticated voluntary-closing designs have been offered in the past by both government supported and privately supported groups, voluntary-opening devices have been provided to an over-whelming majority of upper-limb amputees for many years. Perhaps it is time to evaluate scientifically the successes and failures, be as they may, of the terminal devices that have been available. It is the purpose of this paper to re-examine this very important issue in the light of the experiences of upper-limb amputees during the past 25 years, and re-introduce the debate that might be called "The Terminal Question."

First, it is necessary to understand just how the two systems operate. The voluntary-opening system is one in which the amputee, utilizing relative motion between parts of the human body through a harness-and-cable system opens the fingers of a mechanical terminal device by overcoming a closing, biased force. The voluntary-closing system is one in which the amputee, utilizing a harness and cable, closes the fingers of a mechanical terminal device by overcoming an opening biased force. The two systems thus are exactly opposite in operation.

The fundamental problem with the conclusions of the past debate over the "Terminal Question" was that, for many, the question predicated a single answer: voluntary-opening or voluntary-closing? The lessons the the past have made it apparent that it is more appropriate to evaluate the merits of each system in relationship to the needs and capabilities of the specific segments of the upper-limb amputee population rather than to design a single system which must be effective for all segments of the upper-limb amputee population.

Studies published in the 1970's have estimated the total upper-limb amputee population to be approximately 100,000 persons, (2, 3, 4, 6, 8). Of these, approximately three percent are bilateral and approximately 60 per cent are below-elbow unilateral amputees. These estimates are important inasmuch as they indicate that although unilateral below-elbow amputees represent the majority of the upper-limb amputee population they are, for the most part, wearing the same terminal device as the bilateral amputee or the above-elbow unilateral amputee.

Since the capabilities of bilateral above-elbow amputees, and below-elbow amputees are fundamentally different, the lack of a diverse offering of terminal devices forces amputees to rely on the same voluntary-opening "standard hook." For example, a below-elbow amputee retains the functions provided by the elbow joint and, thus, possesses considerably more "leverage" than the above-elbow amputee. However, the weak and ineffective gripping potential of the voluntary-opening split-hook equalizes the potentials of the two different types of amputations. That is, the below-elbow amputee has no more potential for gripping strength than the above-elbow amputee. Conversely, with a voluntary-closing terminal device, gripping strength increases with the amount of the residual limb. Thus, a wrist disarticulee has greater capability than a 4-inch below-elbow amputee, or an above-elbow amputee. This lack of innovation in terminal device design is as responsible for the degree of disability experienced by the majority of the upper-limb, unilateral below-elbow amputees as the nature of the amputation itself.

Advances have been made in externally powered terminal devices, especially those controlled by myoelectrical signals, but the age of bionics is still on the horizon and no realistic advances for the amputee interested in engaging in strenuous, vigorous activities can be expected in the near future. In fact, at this time, shoulder disarticulees and other patients with severe limb deficiencies can be expected to be the group that could derive the most benefit from externally powered prostheses. What is needed now is a useful option for the majority of the upper-limb amputee population, the unilateral below-elbow amputee. It is important to remember that disuse of the muscles of the residual limb causes atrophy. The greater the length of the residual limb, the greater the need for a muscle powered terminal device.

A literature review revealed that several committees, panels, and books have attempted to answer the "Terminal Question." In *Human Limbs and Their Substitutes* (5), printed in 1954, which is considered by many professionals and educators to be the most definitive text on the subject of artificial limbs, the following conclusions were made regarding the advantages and disadvantages of voluntary-opening and voluntary-closing terminal devices:

1. "Prehension, or the ability to grasp, is the primary function to be sought."
2. Voluntary-opening terminal devices have the advantages of simplicity and do not require a locking device to maintain grip, but voluntary-opening terminal devices have no continuous, progressive range of force controlled directly by the amputee. They are totally insensitive and lack neuromuscular control. Spring tension must be overcome in every operation, and they represent a direct opposite to the normal action of prehension. A living hand and arm does not relax to grasp and then contract to release.

In light of the above criticisms, one wonders why voluntary-opening terminal devices have enjoyed so much popularity and why other designs have not replaced it. The reason is that voluntary-closing devices of that period had problems of their own. However, objections centered around the poor engineering of the existing voluntary-closing terminal devices, and not the action itself. In spite of shortcomings in the existing voluntary-closing terminal devices, the authors concluded:

1. "Yet the voluntary-closing prothesis, if properly developed, offers the possiblity of active amputee control over the amount of grasping force exerted, of furnishing automatic locking of the grasp, and of accommodating the amputee with functional action of the kind found in the natural arm and hand."
2. Finally: "When weighing the considerations, it is apparent that the voluntary-closing terminal devices present the most desirable features, provided only that the engineering problems can be worked out satisfactorily."

The "Advisory Committee on Artificial Limbs" (5) was formed in 1947 to, among other objectives, analyze upper-limb prostheses and to propose solutions to existing engineering problems. The committee, an assembly of professionals, "decided to use the voluntary-closing action in searching for improvements in terminal devices." This committee accepted a set of design criteria which resulted in the development of the APRL hook which included a cam-quadrant clutch, and a two-position thumb. Unfortunately, this new terminal device was unreliable, clumsy to operate, and difficult to maintain in the production model. The failure of these terminal devices is overshadowed by the failure of this committee to analyze and evaluate their mistakes and failure to continue development of voluntary-closing devices. Virtually all research and development in mechanically operated terminal devices ceased at this time and has remained so until recently.

It is important to recognize that the past failures in the design of voluntary-closing terminal devices had been *due to* engineering problems resulting from a conventional set of design criteria and subsequent perception of performance, and not due to the action itself. So, the "Terminal Question" is broader in scope and much more complex than voluntary-opening vs. voluntary-closing. In order to answer the "Question," we must re-evaluate accepted criteria of terminal device design with regard to the specific needs and capabilities of specific segments of the upper-limb amputee population.

In the past, many designs for complete mechanical hands have been proposed. A lack of structural integrity, extreme complexity, and low reliability made these unfit to meet the demands of an active lifestyle. The V.C. APRL hand, the V.C. Miracle hand, the Pecorella V.C. hand, the Becker, and the Trautman V.C. hand are notable examples.

Patent drawings of some of these early mechanical hands such as the Lohmann hand of the 1950's, and the Pecorella of 1950, illustrate the various systems and structural variations designers have used. However, the most predominant design of V.O. and V.C. hooks has been the split hook. The split hook is illustrated by Hosmer-Dorrance hooks, the APRL hook, the V.O. Northrop, the V.O. David, the V.O. Thornton, and the Trautman devices. Since a primary consideration in the design of terminal devices is prehension, it would seem reasonable to consider other hook designs that may represent improvements over the conventional split-hook. For example, the L.A. Caron hook, 1913, and the D.C. Mollenhour, 1947, both attempt to emulate the action of the human forefinger and thumb as opposed to the forceps action of the split hook, and therefore merit consideration.

Two other more exotic designs are the Multiprise hook and the Bottomley Four-bar Link hook. Past evaluations of these devices stated that they had the advantage of prehension over the existing V.O. terminal devices and that their unusual structure was due to an attempt to improve lateral strength characteristics, (5).

With the benefit of this historical perspective, it is to be expected that basic design criteria, and the direction for future development should be readily apparent. But, conventional wisdom and tradition have a way of hanging on in spite of recommendations to the contrary, (5). The

Panel on Upper-limb Prosthetics, 1977 (1), a panel of professionals, met and concluded to perpetuate some of the past mistaken assumptions regarding the design of upper-limb prosthetics. The following is a review and critique of a few of these conventional assumptions:

First and foremost, it is paramount that exclusion of input by the general upper-limb amputee population from initial design considerations be stopped. How can terminal devices be adequately designed without first consulting each specific segment of the upper-limb amputee population with respect to their needs and capabilities? Traditionally, the devices have been designed and prototyped and then the amputees have been asked to evaluate them or a few so-called representative examples of amputees have acted as consultants during the design process and the subsequent evaluation. This represents a fundamental error in research methodology. Finally, too much effort has been invested in trying to discover the panacea of terminal devices, the one and only best terminal device of all. Consideration must be directed toward the specific needs and capabilities of each segment of the upper-limb amputee population. Our review and critique will proceed from this perspective.

1. The highest priority recommendation by the 1977 "Panel on Upper-limb Prosthetics" (1) was: "It is strongly recommended that the delivery of available technology and techniques (e.g., below-elbow myoelectric prostheses) be promoted actively." This is a perfect example of the result of excluding the input of the general upper-limb amputee population from these deliberations, and the subsequently wasteful and expensive "barking up the wrong tree" development program.

   Our interviews with below-elbow amputees have revealed strong opposition to this recommendation, due to the inability of myoelectrics to withstand the elements, the rigors of the vigorous physical activities that below-elbow amputees are capable of, lack of feedback, and the inconvenience of the battery pack on extended hunting and fishing trips.
2. Weight is an obvious consideration. Conventional wisdom tells us that a prosthetic terminal device should be as light as possible. Perhaps, a better set of criteria would include optimum weights for artificial limbs and terminal devices. For example, an above-elbow amputee might require a lightweight device to prevent fatigue, but a below-elbow amputee might require the therapueutic aid of a heavier terminal device in order to restore and maintain the tone of upper-arm musculature, and to provide balance bilaterally to prevent spinal misalignment, (7).
3. Overall size criteria, in the past, have led to the development of terminal devices that are smaller than the normal human hand. Is it possible that the small size lacks the support of amputees? The small size of the "standard hook" limits the size of objects that can be handled, and the bilateral asymmetry and vestigal nature of the abnormally small size may be psychologically demeaning to the wearer. These are questions that need to be put to the amputees.
4. It has been commonly assumed for many years that any "properly" designed V.C. terminal devices should include some sort of automatic locking device. Since a normal human hand cannot lock in place, why should a terminal device? The cam-quadrant lock of the APRL V.C. was rejected by the general amputee population due to frequency and costs of maintenance, lack of durability and reliability, due to poor quality control, high costs, and because it tended to hang up on hard objects since some compression of the fingers was necessary to release the cam-quadrant clutch. Perhaps this criterion requiring a lock should be re-examined. It appears that the belief that all voluntary closing hooks "needed" a locking

device orginated during the time that cineplasties were popular. Genevieve V. Reilly's paper in Physical Therapy Review in May, 1951 stated "The prosthesis must be constructed to provide for special acts of strength far beyond the power of the plastic "motor" itself. This problem is solved through the medium of a lock on the hand." Since conventional figure-eight and figure-nine harnesses do not have the limitations of the cineplasty, these so-called special acts of strength can be accomplished without a lock. A voluntary closing terminal device can easily provide a grasping strength in excess of a normal human hand. Conscious effort in grasping can increase sensitivity and improve muscle tone. However, a manual locking system could provide convenience when prolonged tool use or carrying is necessary, without having the disadvantage of eliminating the rapid release reflex characteristic of automatic locks. Consideration should be redirected toward the use of safe, reliable, and convenient, manually-operated locks.

5. Cosmesis will always be an important factor to consider in prosthetic design. Maybe too much emphasis has been placed on imitative cosmesis in attempts to create a living likeness of a human hand. The smooth surface of the split-hook and its balanced appearance has had much to do with its success. It is not necessary to sacrifice function for cosmesis if a terminal device is designed to be pleasing to the eye like any other precision tool.
6. Versatility to function in a wide range of activities is of utmost importance. Emphasis should be placed on the elimination of the use of special adaptors. Tasks involving complex sequence of events are simply impractical if the amputee has to change special adaptors when the use of a new tool is called for.
7. Finally, the most basic criterion is reliability. A terminal device that does not stand up to shock, torque and abuse from elements is worse than useless; it is a source of frustration and danger. This very important factor is a significant reason to renew consideration of mechanically-operated terminal devices.

There are, of course, many more factors to consider in developing design and performance criteria for prosthetic terminal devices. These have been examples to demonstrate that it is time to face the fact that we do not know all there is to know about designing mechanically-operated prostheses, and that our best source of input about needed changes will come from the amputees themselves. All we need to do is ask.

SUMMARY

We must recognize that the needs and capabilities of upper-limb amputees vary, and that due to a lack of innovation during the last 25 years no successful alternatives have been developed to satisfy the special needs of each segment of the upper-limb amputee population. Outdated design criteria persist in spite of amputee dissatisfaction with the performance of available terminal devices. Since general amputee input has been excluded from the initial design process, it is imperative that a representative sample of the upper-limb amputee population be subjects in a research program designed to establish valid and grounded criteria for the design and development of upper-limb prostheses. This much needed information will finally initiate the development of specific devices to satisfy the needs of specific segments of the upper-limb amputee population, rather than to continue the past practice of trying to develop a panacea for all amputees. Such research will not only correct a long standing and fundamental error in the research process, it will begin the process of designing and developing prostheses that will

encourage upper-limb amputees to live active, independent and more productive lives.

FOOTNOTES

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