A SEARCH FOR BETTER LIMBS: PROSTHETICS RESEARCH AT NORTHWESTERN UNIVERSITY

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HISTORICAL PERSPECTIVE

The Rehabilitation Institute of Chicago established the first private Amputee Clinic in the Chicago area in 1954. In 1958, with financing by the Veterans Administration, a prosthetics research facility was established in the physical facilities of the Rehabilitation Institute by the Department of Orthopaedics, Northwestern University Medical School. From its inception the activities of the Prosthetics Research Laboratory were clinically oriented and dedicated to improving the lot of the amputee, whether he had upper-limb or lower-limb loss. Because of interested clinicians' attendance at the Veterans Administration Regional Amputee Clinic, liaison between the problem veteran amputee and the Prosthetics Research Laboratory was early established.

Early on, the laboratory directed its attention to the area of greatest complaints by amputees, namely the socket-limb interface, and some of the earliest work of the laboratory involved improving techniques for casting and socket fabrication. Suspension casting was one of the techniques which was developed and tested. Many other experimental techniques resulted in definitive procedures that have stood the test of time. Further attention to the same problem resulted in a considerable effort to provide flexible, fluid-filled sockets.

It was early noted also that prosthetic joints required attention, particularly in the above-knee amputee who required not only stability in stance phase, but control of extension and flexion at the knee. The Northwestern variable-cadence knee was one of the early attempts at providing this type of knee function. Due to the large geriatric population of the Rehabilitation Amputee Clinic, a polycentric knee providing improved stance stability was also designed. Improved hip joint alignment control was possible with the Northwestern modification of the hip joint used in the Canadian hip-disarticulation and hemipelvectomy
prosthesis. Several new techniques were developed in fabrication of hip-disarticulation sockets and in the casting of amputees with this difficult prosthetic problem.

It was observed, that the prostheses for upper-limb amputees were also in need of improvement, even though considerable advances had been made since World War II. It was noted that, as one approached the shoulder-disarticulation level, prosthetic replacement was far from satisfactory, in most cases producing only frustration on attempted use. This was particularly acute in the bilateral short above-elbow amputee or the bilateral shoulder-disarticulation amputee. The Michigan feeding arm used by child amputees of the Michigan Crippled Children's Amputee Clinic was developed for this problem. This arm employed electric power and a kinematic coupling technique, coupling elbow and wrist movements, to produce a satisfactory eating function. Adaption of this arm for use by adults was not considered feasible.

The Northwestern ring harness was one of several innovations in upper-limb harnessing. Other items developed for upper-limb problems were a center control hook and a variable lift-tab assembly. Early attempts at providing external power for the upper-limb prosthesis were in the realm of powered assistive devices. These mechanisms were investigated, designed, and subsequently used by several amputees. By 1970 the concept of muscle electricity to provide prosthetic control was also becoming important, and a considerable study was undertaken to improve myoelectric systems, to increase reliability, improve function, and develop simple fitting methods.

Through the years the Laboratory has come to realize the value of close cooperation between the amputee, physician, prosthetist, therapist, and engineer. We feel that this team approach can most effectively attack the problems of prosthetics research and development. Modulation of designs and techniques through interaction of members of this group can keep the work practical and goal-oriented.

**RECENT OBJECTIVES**

Laboratory involvement in upper-limb work during recent years (since 1970) has had a tendency to be self-perpetuating. This apparently has occurred because even minimal success has resulted in the referral to the Laboratory of a number of amputees having special needs or difficult prosthetic problems which correspond vaguely to the work already going on. Consequently, there has been a pyramiding of activity in the upper-limb area. What follows summarizes some of this recent activity. Some of these developments span a period of 2 to 3 years and are considered "medium-range" projects. Other projects are "short range" in nature and may only involve the solution of one problem for one
person. The "short-range" findings are usually not radical departures from existing principles and may not require long development and evaluation programs. Nonetheless, they may be very important in the prosthetic field. Projects which appear to require long gestation periods (5-10 years) are generally investigated outside regular Laboratory activities through interested graduate students of the Technological Institute at Northwestern University. We feel that both long- and short-range research and development are necessary in limb prosthetics.

PRESENT OBJECTIVES

Present objectives of the Northwestern University Prosthetics Research Laboratory are basically as follows:
1. **Develop subconscious control:** In subconscious control the subject controls his assistive device naturally and without consciously thinking about it.
2. **Develop self-suspending and comfortable devices:** Harness and straps are frequently uncomfortable and unsightly and do not provide optimal interface arrangements with the body.
3. **Develop self-contained and cosmetic devices:** Wearers of assistive devices prefer them to be self-contained and simple as well as pleasing in appearance.
4. **Develop high performance and reliable mechanisms:** Mechanisms need to be light, noncumbersome, strong, reliable, and responsive.
5. **Develop rudimentary esthetic qualities in assistive devices:** The disabled person should have a sense of the mechanism as an extension of himself and not as a separate piece of equipment.
6. **Improve existing prosthetic-orthotic components and techniques:** Many disabled people will never use newly developed systems. Improvement of systems which are already well-accepted is important.

**Subconscious Control**

We have tried to use myoelectric control methods as one approach to subconscious control. One interesting result of our studies is that prehension seems to be the function which is most readily adapted to subconscious control through the use of myoelectricity. This seems obvious with the wrist-disarticulation and below-elbow amputee where finger extensor muscles are used to open the hand and finger flexors to close the hand. It may not be obvious that muscles above the elbow joint or above the glenohumeral joint should also be related to prehension. This may be explained by considering what happens when a person grips an object strongly. Muscles of the arm and shoulder all come into play during strong prehension. It is not surprising then when a shoulder-disarticulation amputee reports that contraction of his pec...
toralis major on the amputated side gives him the impression of closing his hand.

We have made use of the contraction of flexor muscles of the forearm, arm, or shoulder areas and their natural relationship with prehension. Therefore, finger flexors and wrist flexor muscle groups are used effectively for subconscious control of prehension by the below-elbow amputees. A typical fitting is shown in Figure 1.

The above-elbow amputee shown in Figure 2 illustrates how the biceps may be used to control prehension. The triceps open the hand. The elbow is controlled by body-power through glenohumeral flexion. We have found this to be a desirable type of fitting for the above-elbow amputee. Other aspects of this prosthesis which should be noted are the open-shoulder construction and the harness (discussed in detail later).

The shoulder-disarticulation amputee shown in Figure 3 uses the pectoralis major to close his artificial hand and the trapezius to open it. Note the use of endoskeletal construction and of the well-fitted minimal-area socket. Endoskeletal construction can be of great benefit to the high-level amputee through the reduction of prosthesis weight.

Myoelectric control can be used effectively at several levels of amputation to develop subconscious control of prehension. The development of myoelectric hand components is therefore proving to be useful for a wide class of upper-limb problems and is not limited to below-elbow cases. It has its greatest advantage when it can be coupled with self-containment and self-suspension as shown in Figure 1.

Figure 1.—Below-elbow amputee wearing a prosthesis with myoelectric control of prehension from the forearm, self-containment, self-suspension (N.U. supracondylar socket), and good cosmesis.
Self-Contained And Self-Suspended Devices

A primary continuing goal of the Laboratory is the development of self-suspension techniques for upper-limb amputation problems. Self-containment is a companion of self-suspension and they should occur together, where possible. We have discussed this in earlier papers (1, 2). The Northwestern University approach to supracondylar suspension has also been presented (3). We feel that atmospheric-pressure suspension will soon be more widely used for upper-limb prosthesis support. Preliminary results with this type of suspension at the wrist-disarticulation and above-elbow levels have been successful, and it appears that sockets which are a combination of hard and flexible material may have significance in this application. A self-suspension socket and prosthesis are shown in Figure 4 as applied to an above-elbow prosthesis of the cosmetic type. This socket has been described in progress reports of our laboratory (4).

Figure 2.—Above-elbow amputee using myoelectric control of prehension from the arm, body-powered elbow, open-shoulder socket, and a thoracic suspension and control harness.

Figure 3.—Shoulder-disarticulation amputee using myoelectric control of prehension from the shoulder, endoskeletal construction, chest strap, and minimal-area socket.

Figure 4.—Above-elbow amputee demonstrates a self-suspending socket which employs atmospheric suspension of a cosmetic prosthesis.
Improvement Of Existing Prosthetic Approaches

We know the so-called conventional upper-limb prostheses of the body-powered variety remain popular and in many cases are the most desirable fittings. These systems came into widespread use during the 1950's and have not been substantially changed since then. This attests to their suitability and to their being somewhat the end product of an evolutionary development. Many of today's amputees will continue to use these effectively for the remainder of their lives. We have, therefore, investigated some possible improvements in these basic systems.

1. Harness for the Above-Elbow Amputee

Figure 5 shows a thoracic-suspension and control harness which is being developed. This harnessing scheme, as shown, harnesses glenohumeral flexion. It is simple and affords the amputee greater comfort and good mechanical advantage when compared with the more conventional "figure-of-eight" harness. The chest strap is more comfortable than an axillary loop. The harness is easy to don and doff. Figure 6 shows the posterior view of this harness arrangement as worn by an above-elbow amputee. Figure 2 shows the anterior aspect.

![Diagram showing harnessing of glenohumeral flexions for above-elbow, body-powered prosthesis.](image)

**Figure 5.**—Diagram showing harnessing of glenohumeral flexions for above-elbow, body-powered prosthesis.
Rotational stability is improved, compared with the "figure-of-eight" harness, in the horizontal plane because of the anterior and posterior attachment of the thoracic-suspension strap. Biomechanical efficiency is improved because the posterior control strap is kept over the inferior aspect of the scapula. The "figure-of-eight" harness may tend to migrate superiorly on an amputee's back during glenohumeral flexion. This results in a loss of power and excursion.

The harness described may be modified for harnessing bicipital abduction. A section of elastic material is inserted in the thoracic suspension strap at the posterior attachment. The medial attachment of the posterior control strap is moved to a point over the scapula on the sound side. This improves the biomechanical efficiency and allows the amputee to utilize both glenohumeral flexion and bicipital abduction for activation of the prosthesis. This is necessary for amputees who have weak glenohumeral flexion.

2. Lift-Lock Mechanism

This work illustrates an attempt to improve function of the dual-cable control system which is so widely used by above-elbow amputees in the United States. They very often use voluntary-opening terminal devices with the result that their ability to lift heavy objects through forearm flexion is limited by opening of the terminal device and not by their own force limitations.

In principle the device functions as illustrated in Figure 7. The control cable passes around a pulley mechanism located where the lift-tab is normally situated. The cable is fixed to this pulley. The pulley is mechanically locked against rotation through a cable attached to the locking bar of the E400 (Hosmer) elbow. When the locking bar is pulled up to disengage the elbow, it pulls a cable which engages a pawl, locking the lift-lock pulley. Cable forces now may be used to lift the forearm, but these forces are not transmitted to the terminal device. Therefore, heavy
objects may be lifted through elbow flexion without being dropped by the terminal device. When the elbow is locked, the locking bar descends and permits the spring-loaded pawl on the lift-lock to disengage. In this condition the pulley is free to rotate, and cable forces are transmitted directly to the terminal device. The unit is shown being worn by an amputee in Figure 8.

The lift-lock also tends to increase cable efficiency. The cable takes essentially the same bending radius at all elbow flexion angles. With the conventional lift-tab the bending radius is substantially reduced as the elbow flexes. Hence efficiency is reduced.

3. Glenohumeral Joint

We have developed a passive glenohumeral joint which solves some of the problems we had experienced with joints at this level. These problems were mainly lack of sufficient holding torque and variation of this holding torque during usage. We call the joint an “orthogonal cylinder glenohumeral joint” since its principle of operation is based upon cylinders which rotate on mutually orthogonal axes. This principle is widely used with tripod heads for cameras and is of rugged, reliable, and inexpensive construction. It permits passive flexion-extension and ab-
duction of the humeral component. It is easily adjustable, will maintain its resistance over a long time interval, and can be set to resist high torque. This is necessary for holding a hunting firearm or other object of considerable weight. Furthermore, it exhibits minimal "stick-slip" characteristics. It is shown in Figure 9.

![Figure 9](image.png)

**FIGURE 9.** View of glenohumeral joint as applied to a shoulder-disarticulation prosthesis of endoskeletal construction.

Despite physical bulk this unit may be used for shoulder-disarticulation cases, as well as interscapulothoracic cases. For shoulder-disarticulation fittings it needs to be mounted below the acromion to achieve good cosmesis. The joint is now commercially available through the Pope Brace Company.

**High Performance and Reliable Mechanisms**

1. *Myo-pulse modulation*

   In 1972 we disclosed a different approach to myoelectric control called "myo-pulse modulation" (5). This technique is used in the commercial VA/NU hand, and we are still involved in the improvement of the hardware which uses this processing scheme. This approach has the following three distinct advantages over previous myoelectric control circuits:
   1. Instantaneous output response to myoelectric input.
   2. Exceptionally good control over a wide range of output velocities or forces.
   3. Simplicity of design.

   In myo-pulse modulation the processing scheme consists only of amplification in conjunction with a small threshold. Positive pulses of the myoelectric signal e(t) are amplified to saturation. Negative pulses are also amplified to saturation with the addition of an inverting stage so
that these output pulses are also positive. The output of such processing is shown in Figure 10. When $|e(t)| > \delta$, the output takes on the value $+V$ volts. When $|e(t)| \leq \delta$, the output is zero. $\delta$ is a small positive number representing the threshold level.

The output, $\gamma(t)$, may be mathematically defined as in equation 1.

$$
\gamma(t) = \frac{V}{2} \{1 + \text{sgn}(|e(t)| - \delta)\}
$$

\text{eq. 1}

where $\delta$ = threshold, $\delta > 0$

$e(t)$ = amplified myoelectric signal

$V$ = d.c. saturation voltage

$\text{sgn}$ = sign function $= 1$ if $(|e(t)| - \delta) > 0$

$= -1$ if $(|e(t)| - \delta) \leq 0$

Experimental results show $\gamma(t)$ may be used directly as an effective input voltage for proportional control of a d.c. motor. Each single pulse is sufficient to overcome "stiction" in the motor and drive system. Consequently, it is possible for single motor unit activity to produce output velocity. This action of a single motor unit is the smallest myoelectric signal which can create movement in the artificial mechanism.

Since only amplification is involved, there is essentially no time delay between input and output. As the myoelectric signal slightly precedes mechanical contraction of a muscle, it is possible for an artificial hand mechanism to actually respond more rapidly to a muscle contraction.
than would the normal physiological hand. Smoothing is accomplished by the mechanical system instead of by electric networks. Kreifeldt and Yao have recently shown that some nonlinear detectors, particularly the quarter-root processor, have superior processing characteristics (6). The quarter-root processor has d.c. transfer characteristics which are similar to those of the myo-pulse modulation scheme described here.

2. Synergetic Prehension

To complement the improved myoelectric controller, a new type of powered prehension device was also devised. It was also disclosed during 1972 (5).

It is well known that essentially no power is required to operate a prehension device. Most of the time the fingers are either moving with velocity at no force or applying force with no velocity. Neither condition requires power.

The Vaduz hand and the Otto Bock electric hand (Z6) have automatic gear shifts so that the fingers are driven in “high gear” at good speed when not opposing a load, and so that they are driven in “low gear” when grasping an object. This approach is desirable, but the mechanisms tend to be complicated and may be slow in shifting back to “high gear” when it is desired that the mechanism should release the prehensile force.

We have suggested “synergetic prehension” as an alternative approach. In this approach two motors operate in a synergistic way to create effective prehension. One small motor and drive mechanism powers one set of fingers at high speed and low torque. The opposing thumb is driven by another small motor at slow speed and high torque. Thus, the former motor provides the speed for closing and opening the terminal device, while the latter produces high prehension forces. Each drive cannot be back-driven.

The principle of synergetic prehension is illustrated in Figure 11. Two electric powered hooks constructed on this principle are being used routinely by below-elbow amputees with good result. One of these fittings is shown in Figure 12. These terminal devices have maximum closing and opening speeds of 4.5 rad./sec. and prehension forces up to 90N (~20 lbf.). They release immediately at any load level.

We feel that the synergetic prehension idea as explained, or in other forms, is valuable in the design of prehension devices.
SYNERGETIC PREHENSION

Figure 11.—In “synergetic prehension” one motor and gear close the fingers while the other motor and gear create the gripping force. The motors function synergetically in the development of prehension.

Figure 12.—A below-elbow amputee wearing a “synergetic prehension” terminal device of the hook type. Myoelectric control self-containment and self-suspension are also employed.
SUMMARY

We believe that socket design is fundamental to the improvement of prostheses. Comfortable, well-fitted prostheses which are self-contained and self-suspended and which have an appealing appearance are basic to improved prosthetic acceptance. Engineering and scientific effort should be expended in the development of lightweight, reliable, and responsive mechanisms which are integral with these basic concepts. Likewise, control should be subconscious for the user and an integral component of the prosthesis. Consequently, prosthetics research and development requires a blending of scientific, technical, and medical ingenuity.

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