Development of Upper Extremity Orthotics

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PART I

RESEARCH AND DEVELOPMENT OF POWERED AND NON-POWERED SYSTEMS

Note: This paper will be presented in two parts. The second section, entitled Patient Applications and Functional Gains, *to be published in the June issue of this journal, will also include the Acknowledgements. Both sections are based on the findings reported in the Final Project Report of the four-year project supported in part by Social and Rehabilitation Service Grant No. RD-1564.*

ABSTRACT

The orthotic systems herein described, developed at Texas Institute for Rehabilitation and Research, have been designed to be functionally efficient, of simplified modular design, economical, durable, and cosmetically acceptable. It has been our experience that these criteria are vitally important to the patient and to the overall usefulness of the orthotic system.

As a result of application to and evaluation of nearly 100 individuals included in the evaluation phase of the project using pneumatically powered systems, it was established that the system affords a practical method in 85% of the individuals for restoring limited but useful hand and arm function for patients with spinal cord lesions at the C-5, 6 level. The finger prehension orthosis with a wrist joint that is friction loaded achieves this objective most efficiently.

This "system" has been designed to use the patient's own skeletal structure and biomechanical functions as an integral part of the orthotic mechanical system. This principle has proved to be very important, because its application avoids a "mechanical man" solu-

tion, and the patient has increased motivation and acceptance of the artificially powered movements which remain under his direct proportional control. This factor is of critical importance if the patient is to be properly assisted in achieving a satisfactory living and vocational adjustment when he is with non-impaired people.

When very few functional residuals are available, such as with the higher spinal cord lesion patients (C-4, 5) the adaptation required is obviously more complex. The mechanical design of the arm unit which was developed provides important missing natural motions so that control of powered assisted movements need be directed primarily to shoulder abduction, elbow flexion, and finger prehension. The mechanical design also takes advantage of the skeletal structure, gravity forces, and mechanical leverage for complementary motions to the powered ones, such as shoulder abduction, elbow extension, and arm pronation and supination. With the powered arm unit, the patient is still able to have useful function restored in a simplified manner that does not leave him overloaded with cumbersome equipment.

In order to improve design criteria for these systems, a kinematic study was undertaken to achieve an objective description of normal movements as they relate to acceleration, velocity, deceleration, and changing angulations. This study was extremely helpful in minimizing discrepancies of motion imposed by the devices themselves.

The functional usefulness in daily living of these powered systems is indicated by the fact that the majority of adaptations thus far made have enabled the quadriplegics participating in the project to increase their activities. Some of the gains made are self-feeding, caring for personal hygiene, writing, typing, handling a telephone, filing papers or cards, and operating a tabulator or computer. Many routinely perform avocational activities such as playing cards or checkers, drawing, or painting. Seven have become gainfully employed, and fourteen others are pursuing education and training directed toward vocational achievement.

While the project was primarily aimed toward the development of powered orthotics, non-powered systems harnessing the patients' residuals into useful function were also developed and found to have extensive utility. These had wider acceptability than was originally expected. The reciprocal wrist extension finger flexion orthosis, designed for the quadriplegic patient with a C-6, 7 lesion who maintains active wrist extension but lacks finger movement, is an excellent example of how remaining muscle action can be effectively utilized. As a result of 450 clinical applications and evaluations, we established that such patients are able to gain considerable functional independence.

INTRODUCTION

Purposes of Project

When the project began in 1964, certain specific proposals were set forth as guidelines. Primary effort was to be devoted to further development and modification of practical, patient-controlled, pneumatically actuated orthotic mechanisms for upper extremities.

While simplicity, functional efficiency, and cosmetic acceptability were the overall objectives, an orthotic system also had to be lightweight; to provide passive structural support to achieve near-normal musculoskeletal alignment, such as in a flaccid hand; and to fully utilize the skeletal articulations as a necessary component of the powered system.

Progressive developments in externally powered orthotic systems indicated a need for detailed analysis of the complex, synchronized musculoskeletal actions in normal upper-extremity motions involved in daily living. The main purpose of this kinematic study was to establish an objective description of normal movements as they relate to acceleration, velocity, deceleration, and changing angulations. The study also identified associated body movements, such as head and torso movements. The findings were extremely helpful in minimizing discrepancies of motion imposed by the equipment.

Although the development of externally powered orthotics was the primary goal, many modifications of existing systems were implemented in the process. These modifications included refinement of the plastic hand orthosis as it is used as a basic module in a systematic approach to correct or prevent deformities or to aid impaired functions. Another important modification was the further development of a reciprocal wrist extension finger flexion orthosis. While each of these was not specifically outlined in the original proposal, each has helped to serve the patients involved.

Facilities and Staff

This project involved many of the professional and non-professional staff and facilities of the Texas Institute for Rehabilitation and Research. Being the operational site of the Department of Rehabilitation of Baylor University College of Medicine, the Institute has specialized in chronic diseases and rehabilitation since its opening in 1959. The Institute has a bed capacity for fifty-five in-patients and facilities for 105 out-patients who are seen in the various clinics.

In addition to the departmental staff, an orthotic advisory board was established consisting of the following members: Dr. William Spencer, Dr. Paul Harrington, Dr. Lewis Leavitt, Dr. George Lane, and Thorkild J. Engen, C.O. Meetings were held routinely with the agenda prepared by the Project Director. The problems, progress, and sequence of developments were discussed, the decisions made were implemented, and the results of these decisions were discussed in follow-up meetings. This arrangement allowed excellent coordination between the various disciplines involved in orthotic research developments.

In conjunction with the project, physiological tests were administered by the Department of Physical Therapy before and after orthotic adaptation, while the patients were trained in the use of their orthotic equipment by the Department of Occupational Therapy.

The patients seen during this research project were referred from the Orthopedic Clinic and consisted primarily of those with high spinal cord lesions, as well as some with a diagnosis of poliomyelitis. Patients who were seen in consultation and for evalution by faculty members of the Departments of Physical Medicine and Orthopedic Surgery throughout the affiliated hospital program were also seen for evaluation and potential application of externally powered orthotic systems in the Department of Orthotics. Through scheduled and nonscheduled clinics, ward rounds, and conferences, the patients were evaluated for pre-orthotic treatment. This early evaluation was to determine if reconstructive surgery or physical therapy were needed to regain the maximum neuromuscular function or to reverse deformities prior to actual orthotic adaptation.

Following adaptation, the patient was followed in the appropriate clinic by members of the medical rehabilitation team for subsequent re-evaluations.

Methodology

In the developmental phase of this research, a number of components were identified as necessary for the basic orthotic systems. Collectively, these components comprise one of four systems: the plastic hand orthosis; the reciprocal wrist extension finger flexion orthosis; the externally powered finger prehension orthosis with wrist friction joint; or the externally powered arm abduction elbow flexion orthosis.

The development of these components evolved from numerous experiments, tests, conferences, and clinical evaluations. The establishment of one component, such as the basic hand module, quite often led to development and modification of other systems.

Plastic Hand Orthosis

For successful restoration of function for a paralyzed extremity, it is important that skeletal alignment be restored, particularly in the fingers and forearm. Early in the project, it was found that it was impossible to restore digital function for a hand with severe muscle imbalance without first realigning the metacarpal arch.

To identify this alignment, an X-ray motion picture film was made of the skeletal structure of normal hands manipulating commonly used objects both with and without the plastic orthosis applied. (Fig. 1)

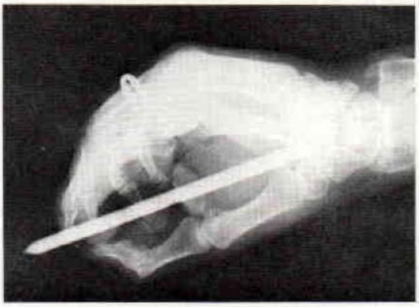

Figure 1

This enabled visual analysis in several planes of the structural skeletal arrangement in various holding and grasping patterns.

This study provided a clearer understanding of the integrated musculoskeletal functions as they relate to normal activities, and served to indicate where support could be given with the least mechanical hindrance to normal functional patterns.

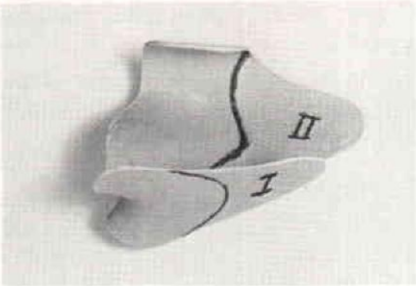

Figure 2

Further modification of the plastic hand orthosis followed as a direct result of this analysis. (Fig. 2) This semi-flexible orthosis, made from molds of various sizes of normal hands, is easily reshaped by heat for individual adaptation. This advantage, plus the incorporation of related components, makes the orthosis adaptable for a variety of patients' needs. (Fig. 3)

The basic orthosis as it comes from the mold incorporates the non-restrictive metacarpal support principle and includes both radial and volar extensions which may be eliminated or used singularly according to the nature of individual adaptations. (Fig. 4)

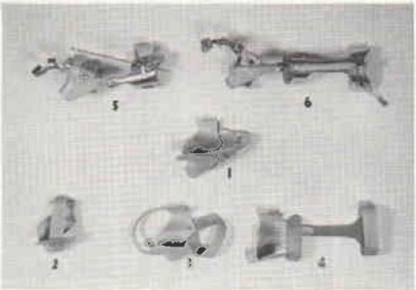

Figure 3

The orthosis may be made into an opponens and metacarpal support by trimming away both radial and volar sections. The addition of a lumbrical support provides another adaptation.

The volar portion of the basic orthosis extends slightly beyond the wrist joint to facilitate attachment of a wrist support. The radial portion extends to the wrist to facilitate the incorporation of a wrist joint when the orthosis used as a reciprocating finger flexion unit.

The plastic shell is now available in four sizes: small, medium, medium-large, and large for both right and left hands. By using the vacuum molding technique, the shells are made from nylon laminated polyester resin using a formula of:

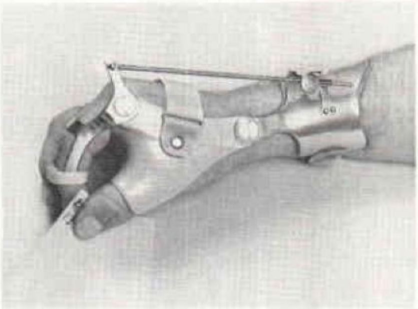

Figure 4

75% Polyester resin 4116 Rigid
25% Polyester resin 4134 Flex
Caucasian epoxy reinforcer
3% Pigment
Approximately 12 drops Naugatuck per 100 grams of resin
5% Luperco ATC
Nylon stockinette

Reciprocal Orthosis

An excellent example of the versatility of the plastic hand orthosis is its use as an integral part of the reciprocal wrist extension finger flexion orthosis. Although this is not an externally powered system, it is a device designed to harness residual motor functions.

The unit is adapted for the patient with active wrist extension but no finger flexion. Through mechanical linkage, the extensor motion is harnessed to provide a useful and practical finger prehension.

When the reciprocal orthosis was first developed, the functional gain was rather limited because of the fixed mechanical range of the unit. As stated previously, the X-ray analysis emphasized the importance of the hand-forearm relationship as functional activities are performed. Based on these findings, an adjustable telescopic rod was developed during the project to expand the mechanical range. (Fig. 5)

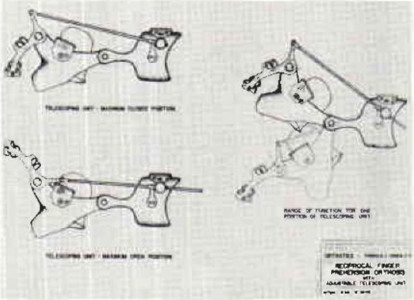

Figure 5

This adjustable rod is activated by the patient's opposite hand or by pressing the activating button against a stable object such as a lapboard. A slight pressure releases the telescopic unit and enables new positioning of the hand. Release of the pressure locks the rod in the new position, thus permitting finely adjusted finger prehension so that a wide range of activities can be performed from holding a cup to picking up paper. With this feature, hyperextension of the wrist and fatigue are greatly minimized when the patient is manipulating small objects.

Patients with relatively weak wrist extension in addition to excessive radial deviation could not achieve a reasonable proportional gain, as the radial deviating movement of the hand in active extension worked against the joint alignment of the orthosis. To solve this problem of mechanical hindrance, a modified, leaf-spring was incorporated in the forearm cuff joining the plastic portion at the wrist. (Fig. 6) This mechanical arrangement permits the patient's biomechanical range of radial deviation to occur in combination with dorsiflexion of the wrist. It was necessary to change the attachment points of the telescopic rod so it would swivel in harmony with the newly incorporated deviation movement. (Fig. 7)

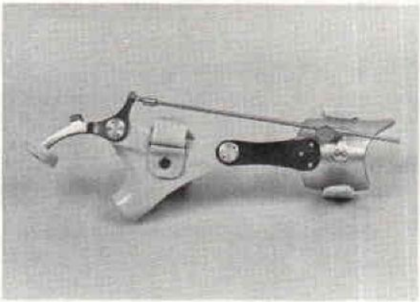

Figure 6

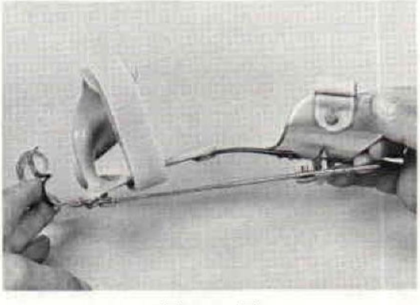

Figure 7

A method of analyzing a patient's residual functional status was also developed in order to achieve optimal matching of a particular device with a particular biomechanical performance. Three factors of primary importance in determining the choice of equipment for restoration of hand function are: 1) degree of residual strength; 2) degree of radial deviation; and 3) range of motion between flexion and extension. A form was developed for recording these three factors, plus the patient's active dorsiflexion of the hands, using a standard muscle test. The radial deviations are recorded, and the range of motion between flexion and extension is determined using standard goniometric procedures.

Externally Powered Orthoses

This project dealt primarily with the development of orthotic systems employing pneumatic power. Two types of orthoses are used routinely for the patients seen at the Institute, an externally powered finger prehension orthosis with wrist friction joint, and an externally powered arm abduction and elbow flexion unit.

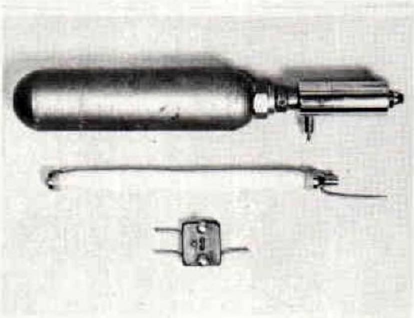

Figure 8

The major components of both systems are the power actuator in the form of the McKibben muscle substitute, compressed carbon dioxide as the power source, and a specially designed control valve for activation. (Fig. 8)

1. **Power Actuator.**—The McKibben muscle substitute is the power actuator used in these orthoses. A variation of the original design which is now used consists of a bladder made of fine grade latex with a diameter of 5/16", two fiberglass helical sleeves, and single groove deeply cut end fittings which are sealed with polyester resin. One end fitting is left open for pressurization.

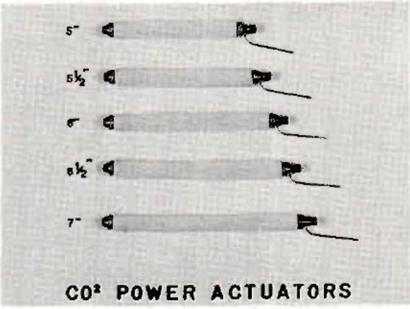

Figure 9

The size of the power actuator itself is determined by the function it is to perform since, for example, the contraction range required varies between finger prehension and elbow flexion. (Fig. 9)

Cycling testing devices were made during the project, and as a result of these efforts, some modifications were made. However, the power actuator still remains somewhat inconsistent in its durability. Extensive research and experimentation was done with different power actuators such as pistons, air bellows, and electro-pneumatic actuators. However, the McKibben muscle substitute was found to be preferable from the standpoint of patient acceptance, due to the smooth, proportionally controllable, combined motions it provides.

2. **Power Source.** — Compressed

carbon dioxide is used as energy for the power actuator. As a power source, it has proved to be practical because it is generally available, the small cylinder can easily be refilled, and it is non-toxic and inexpensive.

When filled with carbon dioxide, the cylinder weighs approximately three pounds. Since all powered applications thus far have been for wheelchair-bound patients, the size and weight of the tank are of little importance. The tank is routinely mounted either on the chair itself or beneath the lapboard surface. A pressure regulator is used to reduce the tank pressure from approximately 750 psi to a working line pressure of 65 psi.

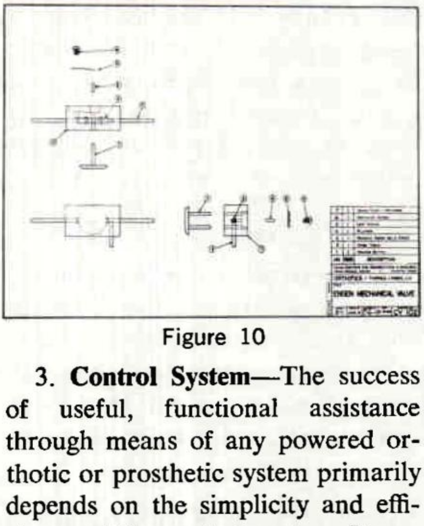

Figure 10

3. **Control System**—The success of useful, functional assistance through means of any powered orthotic or prosthetic system primarily depends on the simplicity and efficiency of the control system. It was determined through patient applications that a mechanical system offered greater simplicity and reliability. Therefore, efforts were made to develop a simple mechanical valve. The detailed report of those efforts was outlined in the final report for project RD-542.

The basic concept has been maintained with only a few modifications. This design resulted in an extremely reliable system which has been used in all patient applications to date. This type of valve also was used in a power actuator testing device and completed approximately 800,000 cycles which is well within the scope of desired durability for this system.

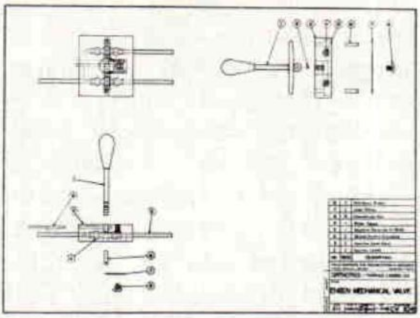

Figure 11

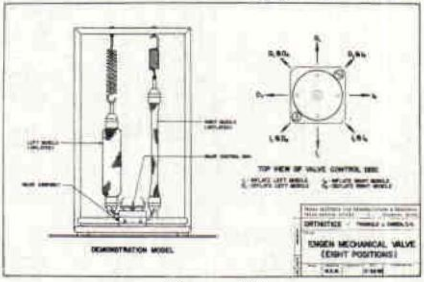

Figure 12

The control valve consists of a flexible silastic tube and a spring-loaded pinching arm capable of depressing the tube sufficiently to stop the flow of gas at a maximum of 75 pounds per square inch. Three basic, lightweight valves are used for patient applications, a single valve (Fig. 10), a double valve (Fig. 11), and a stacked double valve (Fig. 12).

Depending on particular circumstances, it is at times necessary to separate the control for inflation and deflation of the same power actuator. In such instances, two single valves are used. The double valve is used in conjunction with a rocker bar activator and produces both inflation and deflation. The four-way, or stacked, valve is used to control multiple actions. It consists of two double valves stacked together, and permits eight different actions to be synchronized or individualized using a single control site.

The most important features of this type of control valve mechanism are:

1. A line pressure of 65 psi can be controlled by a mechanical linkage of a force of a few grams.

2. Admission and release of gas to the actuator can be controlled by the patient to perform a smooth, gradational movement that is proportional to the controlling action.

3. The valve is leakproof because the flow of gas is controlled from the reservoir to the actuator without internal mechanical interruption of the system.

4. The cooling effect associated with the flow of carbon dioxide does not adversely affect the operation of the system, as the valve will tolerate great variations in temperatures.

5. The material used in the valve will also allow it to be used to regulate the flow of any gas or liquid not corrosive to silastic.

6. The undesirable noise associated with the escaping gas from the deflating actuator is minimized effectively by a small cotton muffler attached at the exit of the deflation tube.

With any powered orthotic application, the control mechanism is located at an individually selected site which is determined by the available voluntary movements. Any slight movement initiated by the patient may be harnessed to activate the system. Care is taken to place the control valve where it will require minimum conscious effort on the patient's part, thus becoming a reflex action within a reasonably short time. The advantage of these control arrangements is that the powered device is not activated accidentally.

Finger Prehension Orthosis

The powered finger-prehension orthosis is designed for individuals with a chronic functional deficit of the hand and wrist, which is seen most often in patients with diagnosed spinal cord lesions at the C-5, 6 level. (Fig. 13)

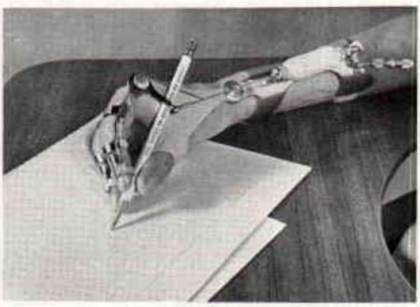

Figure 13

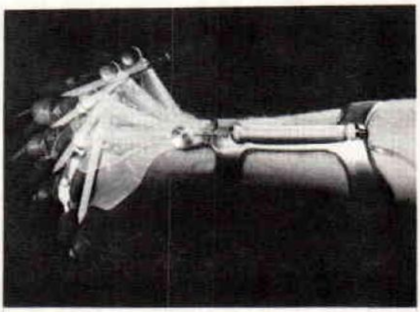

Figure 14

The standardized plastic hand orthosis is used as a foundation for this prehension device. Versatility of function is increased in incorporating a friction joint at the wrist, permitting voluntary prepositioning of the hand in relation to the forearm. (Fig. 14)

A finger unit, which moves the index and long fingers, is hinged at the proximal joint of the orthosis, permitting flexion toward the opposed and mechanically stabilized thumb. A coil spring, also located at this fulcrum point, assists the finger extension movement. The power actuator is located on the radial side of the orthosis. A cable, attached to the distal end of the power actuator, passes through a teflon bushing at the wrist joint and connects with the level arm of the finger piece. Upon contraction of the power actuator, the index and long fingers are flexed toward the thumb.

Figure 15

Occasionally, individual modifications of the powered prehension orthosis must be made to compensate for musculoskeletal problems that interfere with functional activities. For example, patients who hyperextend the distal phalangeal joints of the index and long fingers because of instability are aided when distal finger stops are added to finger unit.

When the problem concerns involuntary flexion of the ring and little fingers, an ulnar guard is attached to the finger unit to prevent these fingers from interfering with functional activities.

Considerable effort has been expended toward the development of a self-contained, lightweight powered finger prehension system designed to be used by ambulatory patients with hand and forearm paralysis. However, these efforts, although promising, never passed the evaluation stage.

Arm Orthosis

The powered arm orthosis is designed for patients who have lost all major function in the upper extremities except the motion of raising and lowering the shoulder girdle. This problem is often seen in post-poliomyelitis patients or those with spinal cord lesions at the C-4, 5 level. (Fig. 15)

The powered arm orthosis consists of two major parts, an abduction unit and an elbow flexion unit. Two power actuators are used in this system, one to flex and supinate the forearm and another to abduct the extremity. These are activated by the patient separately or in combination, depending on the movement he wishes to perform.

The *abduction unit* utilizes the vector parallelogram principle, permitting horizontal movements independent of the powered elevation movement. This system has the following functions:

1. To allow horizontal movements of the extremity
2. To provide vertical movements of the extremity

3. To act as a swivel arm and to support the elbow flexion unit in perpendicular alignment regardless of its elevated position.

A coil spring which minimizes the gravity forces imposed by the extremity is incorporated into the system to assist the power actuator in attaining maximum efficiency.

The *elbow flexion unit* has its fulcrum point located on the medial side of the elbow and corresponds to the axis of the epicondyles. The unit is linked with the abduction unit by means of a swivel arm which has a fulcrum point corresponding to the location of the olecranon. This permits inward and outward horizontal movements of the forearm.

A telescopic rod and tube connected to the flexion unit serves as an attachment for the hand support and also allows voluntary pronation and supination. The proximal end of the power actuator is located slightly above the fulcrum of the elbow joint, and the distal end is attached near the radial side of the orthosis.

The shoulder abductor and elbow flexor components are made from stainless steel. Teflon, needle thrust and roller bearings are incorporated in the joints to produce low frictional resistance. A molded elbow and forearm trough made of laminated polyester resin is attached to the unit. A cutout is located at the olecranon to permit firm seating of the elbow and prevent the forearm from sliding when the elbow is fully flexed. This is very important because of the critical location of the fulcrum points of the unit, which must correspond closely with those of the extremity. The forearm is stabilized in the trough with a Velcro strap.

Kinematic Studies

To establish improved design criteria for the artificially powered arm movements, the kinematic studies were undertaken to achieve an objective description of normal movements as they relate to acceleration, velocity, deceleration, and changing angulations. This study was extremely helpful in minimizing discrepancies of motion imposed by the devices themselves, and was initiated in collaboration with the staff of the Bioengineering Laboratory, Veterans Administration Prosthetics Center, New York.

Staff members from the center served as the normal subjects. Those who were chosen as subjects ranged from slightly obese to tall, thin individuals. Nine subjects were filmed while performing five basic functions of table-to-mouth feeding, hair grooming, page turning, writing, and diagnal reaching. These activities encompass the three important levels of hand movement, table, mid-torso, and head, utilizing the most functional range of motion of an upper extremity.

A 35-millimeter, 25-frame per second movie camera was used and placed 20 feet from the subject. Two mirrors were positioned at 45-degree angles to show three perspectives of the subject simultaneously: front, side, and top. Time clocks indicating one second and one-hundreth of a second intervals provided references for the indication of velocity and acceleration of each motion as reflected in change of position of reference landmarks during fixed intervals of time.

A black felt pen was used to identify landmarks on the subject at the metacarpophalangeal joints, the styloid processes, the lateral epicondyle of the elbow, and the shoulder joint. The tip of the nose was used to record the head movements.

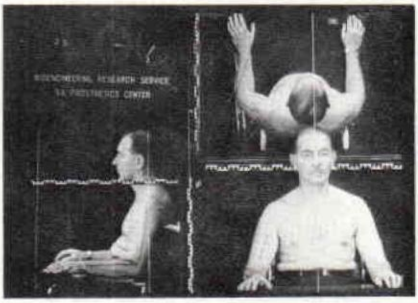

Figure 16

For comparative purposes, two identical sequences were taken of each subject, first *without* orthotic equipment (Fig. 16), and second, with the arm othosis but without the use of external power (Fig. 17), to determine if the equipment hinders normal upper-extremity movement. Recording mechanisms were not placed directly on the subjects to insure minimal mechanical hindrance being imposed on the extremity.

The negative film was made into a positive print in order to obtain a clearer image. A special mirror arrangement and a standard film strip projector were used to project the three perspectives of the subject on to a glass screen which also served as a viewing table. The screen was covered with tracing vellum to facilitate plotting. (Fig. 18)

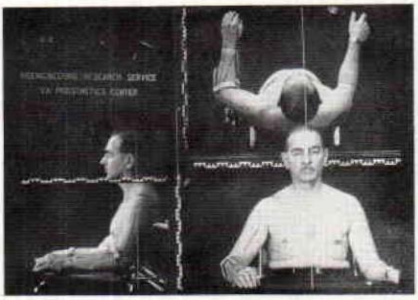

Figure 17

Figure 18

The selected landmarks were identified in each frame in black on the vellum. Once the action was analyzed, the points were connected with black lines to identify the pattern of movements, and the relating angulation and acceleration between each point. The time interval between each connected point remained constant at .13 second.

Photographs were then taken of the completed diagram which was superimposed over both the beginning and end motions for each activity. (Fig. 19) This represented a single plane, rectangular coordinate

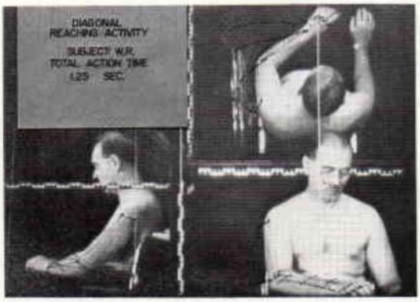

Figure 19

projection of landmarks that are, in fact, being rotated spatially during the real movement.

While this report is not intended to discuss skeletal anatomy in detail, but is instead an attempt to identify the sequence range and gross pattern of biomechanical actions, it should be kept in mind that the resulting diagrams are visual and are approximate data reductions of extremely complex and finely synchronized multiplane upper-extremity movements.

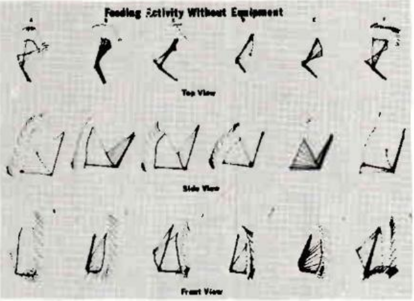

Chart 1

These limitations must be accepted because of the difficulty in externally locating the precise center of rotation of movements in a particular subject. In particular, the axes of shoulder and head movements and supination and pronation of the forearm cannot be located precisely because of the arrangement of the skeletal joints and differing location of various articulating structures within muscle tissue among individuals.

Despite these difficulties, the plots illustrate the character of synchronized, biomechanical articulations as purposeful, functional activities, which are performed both with and without the orthotic arm unit applied.

Because of the massive volume of data available from photographic techniques, two typical examples were selected from the nine subjects for this discussion. This resulted in four diagrams of the five typical activities both with and without the arm unit. For simplicity in comparing the various activities, the diagrams were correlated within each activity according to the view represented: top, side, or front. The two diagrams for each subject were then compared in order to identify evidence of mechanical hindrance or interference, or differences in the pattern of the movement as compared to the normal degree of upper-extremity freedom, which may have been imposed by the orthotic arm unit.

As an illustration of the data obtained from one activity, the diagrams of six subjects engaged in the *feeding activity* are presented in *Charts 1 and 2*.

In comparing the data from each subject, certain similarities of motion patterns are evident which are characterized by the range and angulations of each joint motion.

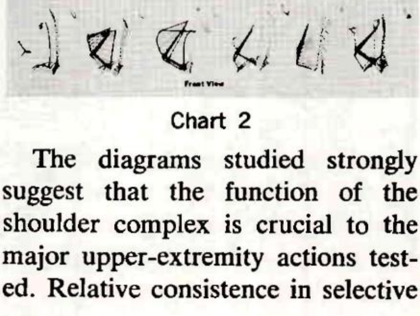

Chart 2

The diagrams studied strongly suggest that the function of the shoulder complex is crucial to the major upper-extremity actions tested. Relative consistence in selective

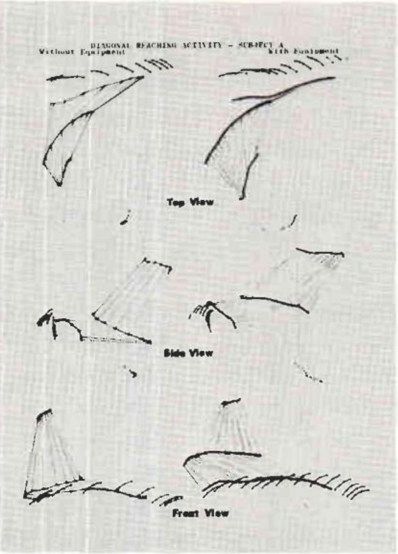

Chart 3

joint fixation is also evident as a vital part of whatever activity is being performed.

Joint movements and/or joint fixation is apparently finely synchronized by eye-hand coordination, as evidenced in the characteristics of *diagonal reaching* performed by two typical subjects in *Charts 3 and 4*. In this important function, the major movement occurs in the shoulder complex, consisting of elevation, abduction, and forward rotation. It is noted in all views of this activity.

An excellent example of selective joint fixation is also illustrated in this activity. The position of the hand and forearm and the angle of the elbow remain fixed throughout the subjects' performances without equipment.

In comparing the functions with equipment, the performances of subject A appears to be almost identical in timing, eye-hand coordination, shoulder movements, and wrist, forearm, and elbow positioning. Some differences are noted, however, in the performance of Subject B in all three views with equipment. In order to minimize the gravity forces imposed on a flaccid extremity, dynamic assistance is routinely incorporated in the arm orthosis. This arrangement does provide some degree of assistance, which is quite evident in comparing the two sets of data on Subject B.

One of the most desirable functions that a quadriplegic wishes to perform is that of *independent writing*. This is an activity which can be avocational, but often evolves into vocational endeavor.

The subjects used in this study were instructed to pick up the pencil from the lapboard, position it properly, and begin writing in their normal fashion. The diagramatic patterns demonstrate an expected uniformity between the individuals in *Charts 5 and 6*. In particular, the sequence of joint movements in-

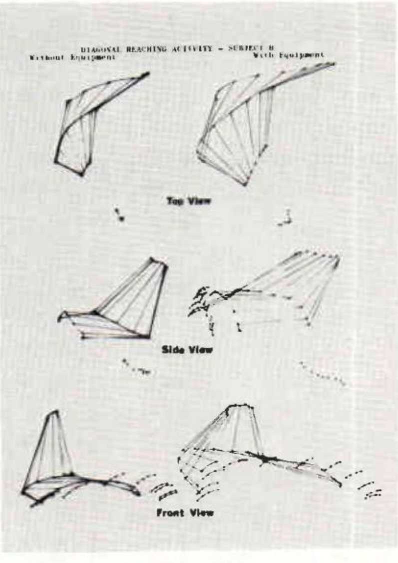

Chart 4

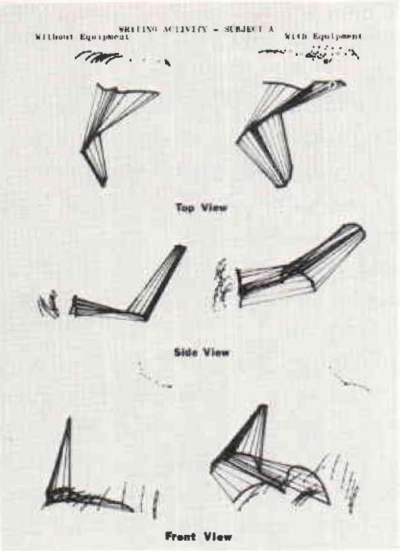

Chart 5

cludes shoulder rotation and elevation, head movement, slight wrist movement, and a considerable degree of supination while the elbow remains in a semi-flexed position throughout the activity.

In comparing the two sets of diagrams, a combination of mechanical hindrance and mechanical assistance is evident. The weight of the forearm is minimized by the dynamic assistance given by the arm orthosis as it was in the diagonal reaching activity. Some mechanical hindrance is noted, however, in the important wrist function. This is caused by the device itself not allowing wrist movement. As a result of these findings, a mechanical wrist friction joint was incorporated in the arm orthosis, thus permitting a patient using this type of device to voluntarily preposition the hand-forearm alignment which is so important to writing.

In *page-turning activity,* the eye-hand synchrony is clearly illustrated in the front view, as shown in *Charts 7 and 8.* In the diagrams for both subjects without equipment, the functions were performed with the major movements occuring in the shoulder complex as seen in diagonal reaching *Charts 3 and 4.*

When comparing both subjects' performances with equipment, the patterns of movements appear less coordinated with increased shoulder motion and a time lag which may be caused by frictional problems.

The *hair grooming function,* as shown in *Charts 9 and 10,* includes the range of motion needed for neck and facial hygiene. This activity employs the greatest motional range of synchronized articulations of the various skeletal joints composing the upper extremity and upper torso of all functions studied. In comparing the subjects' diagrams, the performance with equipment is slightly different. A maximum range of elbow flexion is necessary to bring the hand to the upper facial

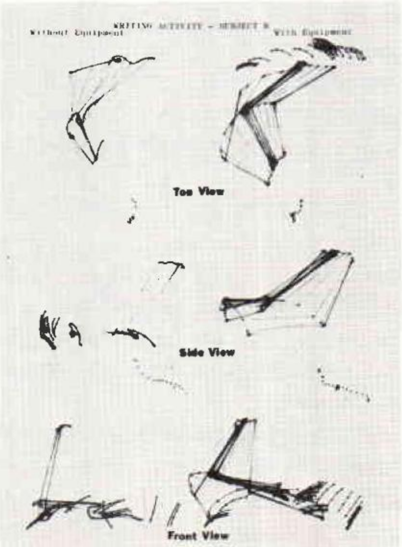

Chart 6

area in order to perform the function of hair grooming with the arm unit in contrast to the more closely organized normal movement. Some mechanical restraint imposed by the arm orthosis is also identified in this activity.

In the studies of *feeding activity, Charts 11 and 12,* a significant difference (which may be due to heredity reasons) was noted between the normal subjects performing the same type of feeding activity. In this action alone, the variation in physical stature and acquired cultural styles of feeding cause significan natural variations in the pattern of self-feeding. This is the most obvious when, for example, there is an excessive forward head movement, showing an anticipation of the arrival of the loaded feeding instrument as an integral part of the overall feeding movement.

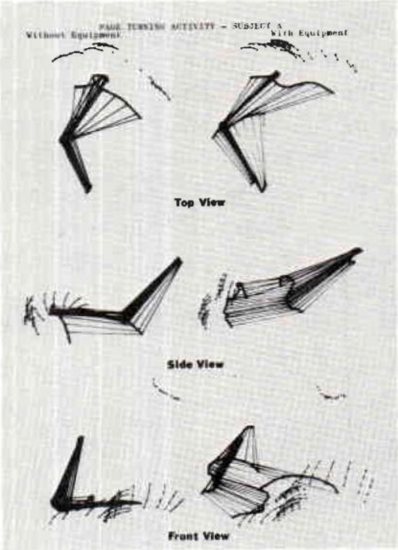

Chart 7

A normal feeding function is accomplished by a complex synchronization of shoulder abduction, elevation, internal rotation, scapular abduction, elbow flexion, and hand supination. In comparing the action with equipment, it should be noted that the elbow flexion has been replaced in some instances by the need for increased shoulder elevation, which then prolongs the pattern of the extremity action to some degree. Despite these differences, the arm orthosis still permitted these complex skeletal articulations to be performed by each subject without major mechanical hindrance as illustrated by the more complete graphs *Charts 1 and 2* showing six subjects' diagrams. Also, the device tended to force the subjects into a more comparable pattern of movement.

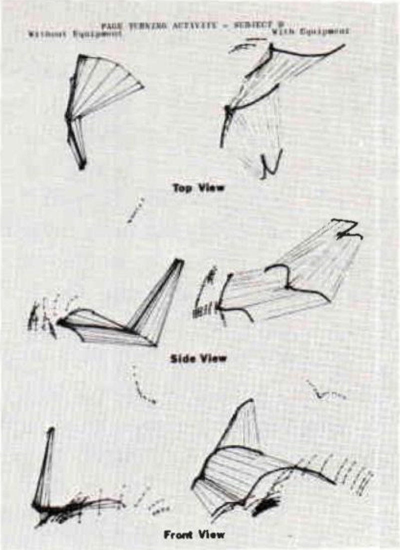

Chart 8

In summary, this study has been useful in identifying, diagramatically and graphically, the biomechanical actions of synchronized, coordinated eye-hand movements occuring while common, normal upper extremity functions were performed by usage of a new and simple form of data reduction. Based on the information gained, a more realistic understanding of the mechanical requirements needed for functional substitutes for the quadriplegic patient has been achieved, and some were implemented in equipment design revisions. In addition, it also appears that the findings may be useful to the field of prosthetics.

The shoulder joint, with its magnitude of multiple extremity position combinations, appears to be extremely important to preserve and to actively utilize in consideration of prosthetic equipment design. Movements in that area are spatially amplified at the terminal point of the hand. Potentially useful residuals in the scapular area in a shoulder disarticulated patient are often immobilized or minimized because of the method of suspending the prosthesis from a rather rigid torso plastic shell. This study would indicate that this is undesirable.

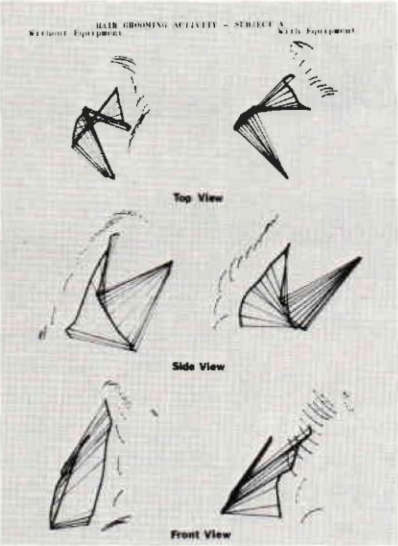

Chart 9

Furthermore, it is evident that functions, such as those studied, which are performed from a sitting position require, in fact, minimal active elbow movement. Based on this observation, it appears feasible to design a free elbow with an instant easily operated locking mechanism which would allow the amputee to pre-set the angulation of the elbow to correspond with the requirements of the kind of activity being performed. Also, it appears that greater effort should be directed toward providing powered assistance in the area of supination and pronation and flexion and extension of the wrist in order to allow a "fine-tuning" of the gross movements provided by the shoulder complex.

With the massive data available from this study, further analysis appears to be not only possible but also practical. While it was beyond the scope of this project to continue

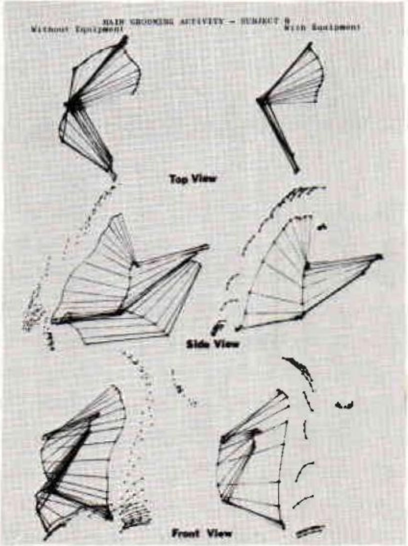

Chart 10

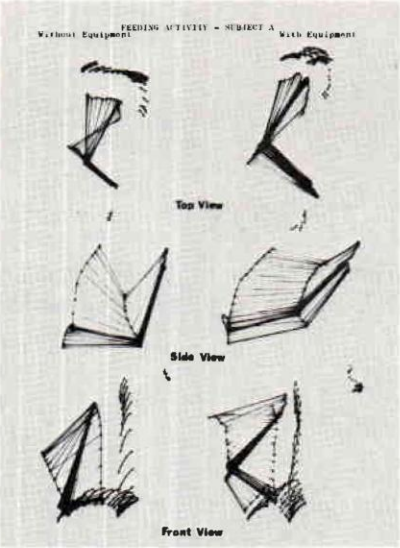

Chart 11

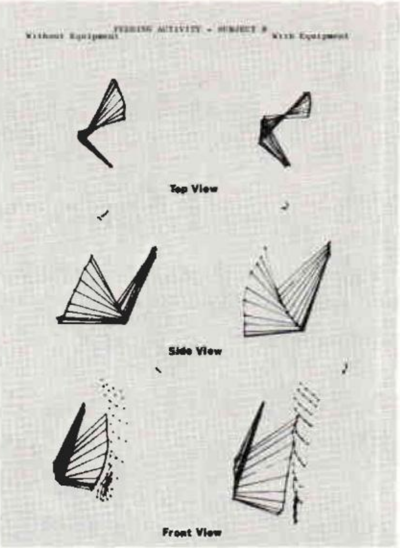

Chart 12

this analysis in depth, it is recommended, however, that further study and analysis of this kind be implemented and given research priority.

A useful methodology has been developed and evaluated which should provide a basis for improved design of orthotic and prosthetic devices and permit data collection of the effect of mechanical designs based on natural movement patterns, once these patterns and their variences are properly identified.

This approach to design follows the philosophy that, initially, it has been valuable to concentrate on providing a limited number of useful upper-extremity movements rather than providing a system permitting all degrees of freedom encountered in the natural movements. Such an approach can be expanded in terms of degrees of freedom as new methods of control are refined.

This first portion of the paper has to some degree summarized the most important aspects in the development of powered and non-powered upper-extremity orthotic systems under project RD-1564. Part II will concentrate on the functional gains achieved by patients with various physiological impairments using the systems described in Part I.

LEGEND:

Figure 1. One movie frame of a normal hand holding a pencil, showing the structural arrangement of the metacarpophalangeal joints.
Figure 2. Basic orthosis which included radial and volar extensions.
Figure 3. Plastic hand orthosis (center) and its use in various orthotic systems.
Figure 4. Reciprocal wrist extension finger flexion orthosis.
Figure 5. Diagram of the reciprocal orthosis with the adjustable telescopic rod.
Figure 6. In order to reduce mechanical resistance, a leaf-spring was incorporated in the forearm cuff joining the plastic portion at the wrist.
Figure 7. Attachment points of the telescoping rod were made to swivel in order to permit radial deviation.
Figure 8. The major components of the externally powered systems are (from top) the power source, power actuator, and control valve.
Figure 9. The power actuator used is available in varying sizes, depending on the function it is to perform.
Figure 10. The single valve, weighing 4.5 grams, is used to control either inflation or deflation of the power actuator.
Figure 11. The double valve weighs 8.2 grams and produces both inflation and deflation.
Figure 12. Diagram of the stacked valve control system which weighs 19 grams.
Figure 13. The externally powered finger prehension orthosis with distal finger support as used in a functional activity.
Figure 14. Incorporation of a wrist friction joint permits voluntary pre-positioning of the hand in relation to the forearm.
Figure 15. Powered arm abduction elbow flexion orthosis.
Figure 16. Mirrors were used to show front, side, and top perspectives of the subject simultaneously.
Figure 17. A second sequence was taken with the arm orthosis but without the use of external power for comparative purposes.
Figure 18. A special mirror arrangement and a standard film strip projector were used to project the three perspectives of the subject onto a glass screen.
Figure 19. Photographs were taken of the completed diagrams which were superimposed over the beginning and end motions of each activity.