Development Toward A Controllable Orthotic System For Restoring Useful Arm and Hand Actions

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INTRODUCTION

Cumulatively over recent years an increasing number of patients are surviving with extensive paralysis which includes loss of hand and arm movements in both upper extremities. This situation occurs in persons with high cervical cord lesions (C-5, C-6) who have survived traumatic injury with quadriplegia, as well as in persons with severe poliomyelitis residuals, those with central nervous system degeneration, disorders of the spinal motor system, and persons with myopathies. Among these, a large number are wheel chair bound for life, and they present diverse patterns of bilateral muscular weaknesses and paralysis of the upper extremities. These patients are a unique challenge to the combined efforts of physicians, orthotists, and other specialties to restore useful functions through application of suitable assistive mechanical devices. The fact that this challenge exists and that efforts to meet it are delinquent was recognized and described in the report of the 1962 *Conference on Orthotics Research and Development* issued by the National Academy of Sciences.[1] Upper extremity orthotics requires intensive development through multiple research and varied study approaches, if we are to meet eventually the great variety of needs encountered among these types of patients.

This report presents information on the most recent developments pertaining to a simple yet extensively useful upper extremity orthotic system, which resulted from a three-year research project carried out in the Department of Orthotics at the Texas Institute for Rehabilitation and Research and the Baylor University College of Medicine. A principal objective in developing this system is to restore hand and arm actions to wheel chair bound quadriplegic patients, and others of comparable handicap, having essentially flaccid paralysis in various patterns and degrees. Advantage is taken of the wheel chair as a frame of support for the external mechanisms, thereby minimizing the number of devices attached directly to the patient. A simplified pneumatic system subject to control by the patient was developed. This approach not only has definite cosmetic appeal, but also gives the patient a feeling of dignity and existence through his direct participation both in the control of the source of power and in being a consciously active part of the orthotic system.

BASIC OBJECTIVES

The developments to be described cannot be viewed as consisting solely in the mechanism. Equally important is the point of view taken by the orthotist in determining the direction of the developments and in evaluating the motional components that accomplish the desired and useful total

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actions that are serviceable to the patient. These latter factors will be discussed first, because they are an integral part of the research achievement and gave direction to the course taken in evolving new mechanisms.

At the outset, one must be aware of the great diversity in varieties and degrees of bilateral involvment of the upper extremity muscle systems presented by patients with cervical cord lesions, for example. Consequently, requirements for restoration of useful actions differ markedly between individual patients. Each patient to be considered for this orthotic system must be carefully examined and analyzed kinesiologically to determine patterns of function that remain, the relative degrees of strength and usefulness of the principal muscles serving the desired integrated actions, and where the severe losses are located. The patient must be able to tolerate the sitting position at 80° to 90°. The presence of joint tightness and muscle spasm exclude a patient from being an acceptable candidate for this orthotic system until these conditions are relieved or minimized medically.

Several factors were formulated explicitly as basic criteria in the ultimate objectives for a practical achievement, and certainly these considerations are of foremost importance in all orthotic efforts. In respect to the mechanical design, both construction and operation should be held to the utmost simplicity that is consistent with achieving functional objectives. Durability of parts, accuracy of operation, and economies in costs are of equivalent importance. Our practical experience has shown repeatedly the futility of imposing upon a patient complicated mechanisms that make him a passive robot and do not serve proportionately useful purposes. Such mechanisms will not be used continuously or effectively if the patient can find privately any other way out, even when this choice may involve reduced function.

PRACTICAL REQUIREMENTS

Since our ultimate aim is to serve a fairly large patient population, many of whom cannot visit a rehabilitation center where expert services are available, components should be designed for mass production and modular fitting to the fullest extent. To attain patient acceptance and pride, cosmesis and comfort are important considerations always. To make the patient happy as well as alert, every design should permit maximum participation by the patient in controlling and producing the useful actions. Finally, a carefully planned program to orient the patient to the versatility of the orthotic system and to provide practical training as indicated in producing useful activities and having successful and gratifying experiences with the system are necessary to insure progress, satisfaction and continuous usage. All of these considerations served to guide the direction of the mechanical devlopments in the present orthotic system, and indeed will continue to be primary factors for inclusion in any future developments of this nature.

Because of these basic criteria for development objectives, critical analysis and early rejection were given to the general ideas underlying the concept of attempting to imitate the actual detailed *motional components* produced during usual activities of normal muscle systems. This approach leads to unduly complicated hardware and control mechanisms, and provides for many actual motions that can be eliminated without reducing useful services to the patient. The traditional law of diminishing returns applies here, since the gain in useful actions is not proportional to the increase in individual motion components and the parallel increase in complexity of the mechanisms. Consequently, the initial concept adopted for this research development was to determine an optimum number and kind of *useful actions*, and then study the simplest means of enabling the patient to ac-

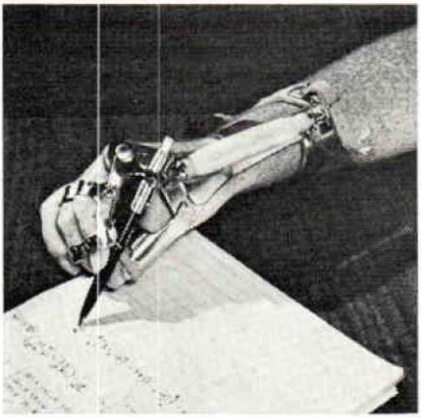

Figure 1—Powered hand orthosis providing finger prehension.

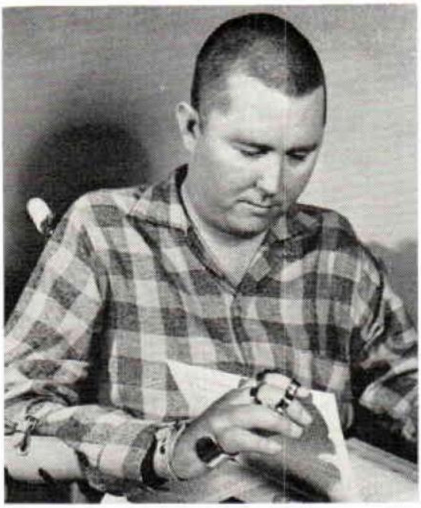

Figure 2—Powered system combining finger prehension—Elbow flexion and shoulder abduction.

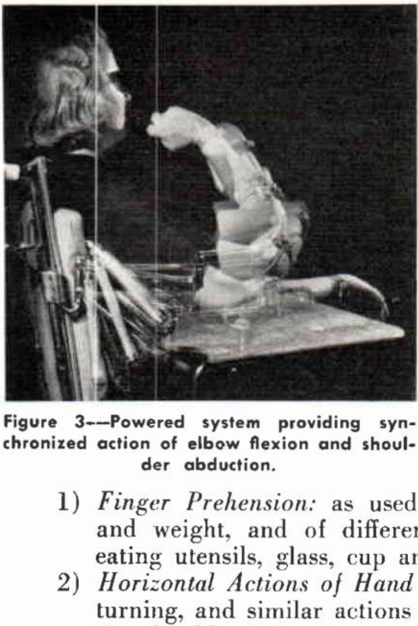

Figure 3—Powered system providing synchronized action of elbow flexion and shoulder abduction.

complish these actions. Three exceedingly useful and fundamental actions are described here, although for the future additional ones may be considered, when the real need for them becomes apparent.

The three principal actions considered to be most useful and which comprise the hand and arm actions that may be restored by the proper application of the present orthotic system are the following:

1) *Finger Prehension:* as used in grasping objects of moderate size and weight, and of different shapes, such as pencil, pen, paper, eating utensils, glass, cup and similar objects. (See Figure 1)
2) *Horizontal Actions of Hand and Forearm:* as used in writing, page turning, and similar actions not requiring major forceful actions at the shoulder joint that can be imparted by slight head and trunk position shifts.
3) *Synchronized Actions of Forearm and Upper Arm:* yielding smoothly phased and finely controlled combined motional components to produce natural and useful actions. The component motions produced include elbow flexion; partial supination and pronation of the forearm; shoulder flexion, vertical abduction, horizontal abduction, internal and external rotation. The useful actions include feeding, head and neck hygiene, applying makeup, brushing teeth, shaving, smoking, and similar actions. (See Figure 3)

In addition to these actions and unique to this system, motions may be arrested at any phase of their course providing thereby a fixed positioning for a useful purpose such as holding an object in a desirable location without expending energy.

DEVELOPMENT OF MECHANISM

A rather unique approach was used in the final stages of arriving at the essential principles underlying the mechanical components of this orthotic system. During this research project, there were forty-one different designs or combinations of components tried out in a sequential effort to evolve an approach that is really practical and useful to the patients. During each stage some progress was in evidence, but the major advance occurred at about experiment No. 38, when an entirely new idea evolved. From this, the present system was developed rapidly. Nevertheless, all of the preceding experience was contributory.

The procedure which helped most in arriving at the concept employed in this orthotic system was as follows: A normal subject was placed in a wheel chair and mechanical components were made and applied to one of his upper extremities. These devices were attached to the wheel chair for support. The subject was required to perform numerous natural actions of the upper extremity without being opposed by the mechanical system. Changes were made from time to time until the mechanical system corresponded with the antomical structures and the multiple joint systems, so that gradually the normal motions and the mechanical system were smoothly synchronized.

Following this, a patient with a flaccid upper extremity and approximately the same size as the normal subject was placed in the same equipment and chair. Our next step was to apply power to the system so the desired actions of the extremity would result in a manner equivalent to those of the normal subject. The McKibben Muscle Substitute was attached to the mechanical device using as much as possible the pattern of origin and insertion points of normal muscle structure. In early experiments, the biceps principle was used to bring about flexion of the elbow joint, but the power actuator was later relocated along the forearm copying the action of the M. Brachio-radialis. This arrangement simplified the entire design, because mechanical support was no longer needed on the upper arm for a power attachment. In addition, it permitted the important abduction function of the shoulder joint, independent of or combined with elbow flexion. As a consequence of this arrangement, the patient's upper extremity has to function as an essential mechanical link in this system.

Three types of integrated forces are used to activate the orthotic system.

CO_2 Actuators   Spring Forces   Gravity Forces

For the purpose of simplicity, the components necessary in the power system are divided into three groups and briefly discussed.

1) Power Actuator   2) Energy   3) Controls

POWER ACTUATOR

The power actuator we have chosen to activate the orthotic components is the McKibben Muscle Substitute. The function of this device has been well described in several previous publications.[2]

During our experience with this actuator, we have found it useful in our latest adaptations to modify the size of the artificial muscle according to the work it is to perform. This is because the energy and power necessary to provide adequate finger prehension is much less than the power needed, for instance, in shoulder abduction. Furthermore, incorporation of two helical woven sleevings in one muscle unit was found to increase the durability with little or no sacrifice of performance. The end fittings and method of attachment to the mechanical system are modified and sealed in plastic according to the function it is to perform. (See Figure 4)

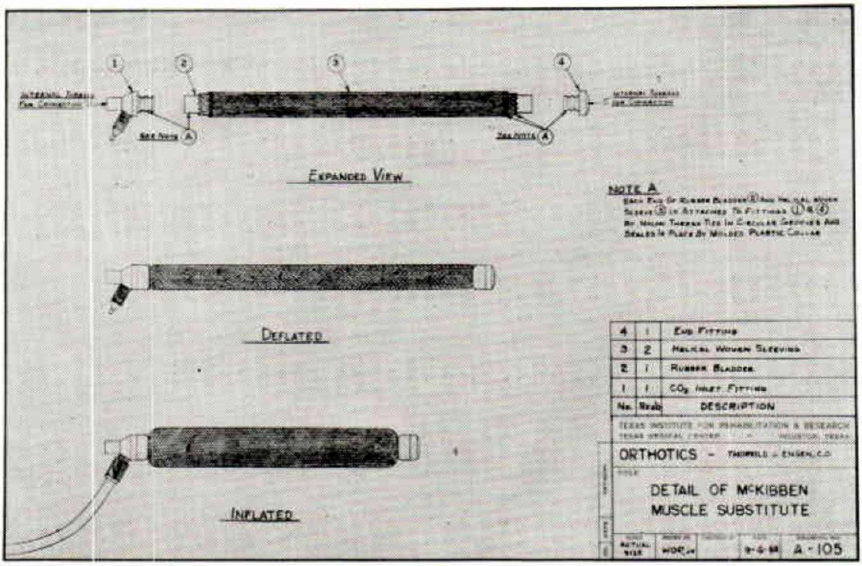

Figure 4—Modified McKibben Muscle Substitute.

ENERGY SOURCE

Carbon dioxide has proven to be practical as a power source for the above described actuator primarily because it imposes no hazard to the patient, it is generally available, and not as expensive as other energy sources. Large tanks of CO_2 with an inside siphon tube can be rented from various supply companies for the purpose of refilling smaller containers.[3] Small throwaway cartridges used in making carbonated water have shown potential usage as an energy source for a self contained powered finger prehension orthosis.

CONTROL SYSTEM

The success of useful actions obtained through means of powered orthotic systems adapted to the patient largely depends on the simplicity and efficiency of the control system. Furthermore, it is desirable that the patient be in control of the system and not the system in control of the patient. The rate and extent of response should be proportional to the controlling action.

A new principle was utilized in developing a simple valve for this control system. This consists of a flexible silastic rubber tubing*, and a spring loaded arm capable of depressing or pinching a cross section of the silastic tube sufficiently to stop or permit the flow of gas under pressure.[4] As a permanent enclosure, the valve mechanism is imbedded in a plastic casing made from polyester resin. The functions of the valve can be studied in detail in Figure 5, which shows a double action push button valve; in Figure 6, a double action control stick valve; and finally in Figure 7, a single action push button valve.

The type of control valve selected for an individual patient is determined by the control site available. 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, single valve units are used.

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* Medical Silastic® 372—tubing .045″ x .105″.

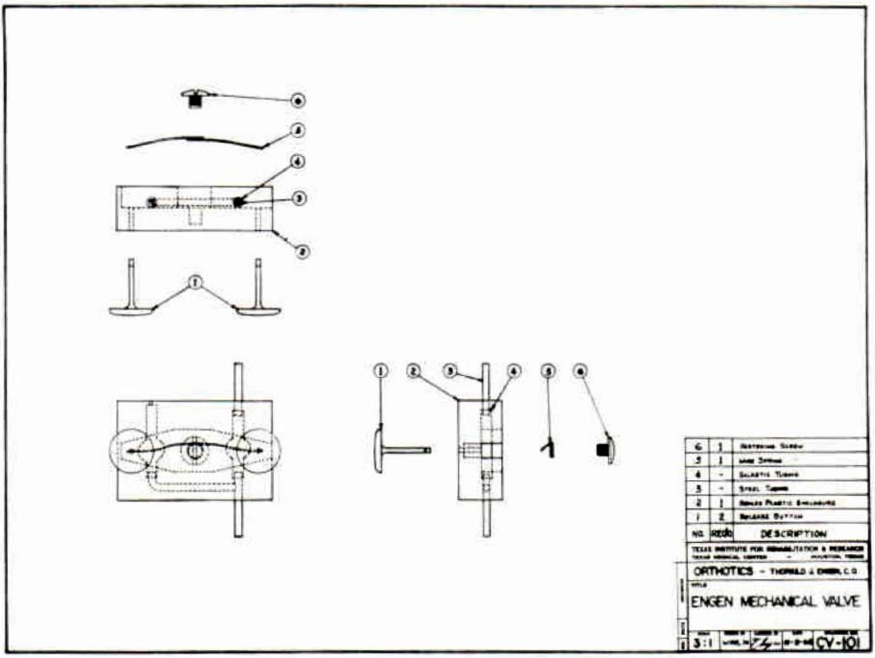

Figure 5—Double action push button valve.

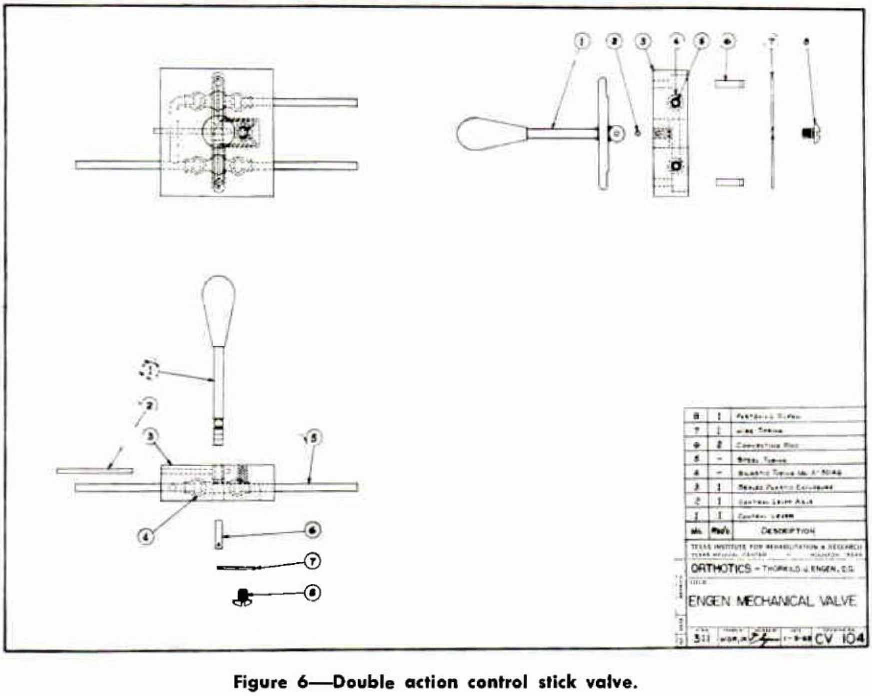

Figure 6—Double action control stick valve.

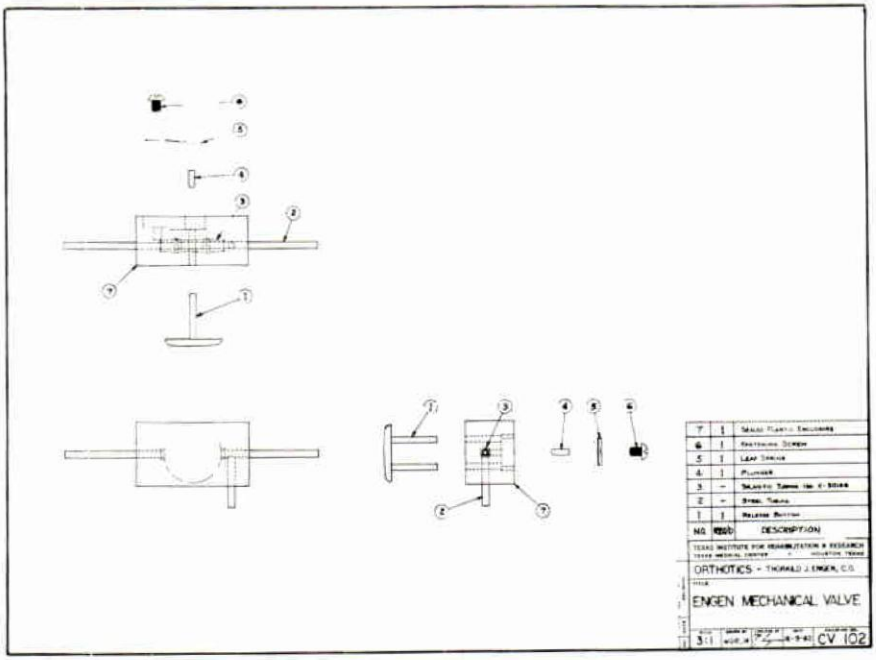

Figure 7—Single action push button valve.

IMPORTANT FEATURES OF THE CONTROL VALVE

1) A line pressure of 80 psi can be controlled by mechanical linkage of a force of less than one ounce.
2) Admission and release of gas to the actuator can be gradated by the patient to perform a rapid response, and either a fast or a slow action may be provided according to the motion desired.
3) It is leak proof because the flow of gas is controlled from the reservoir to the actuator without internal mechanical interruption of the system.
4) The double valve weighs 9 grams, and the single valve weighs 5 grams. The physical size is comparable to a man's wrist watch.
5) The cooling effect associated with the flow of carbon dioxide does not adversely affect the operation of the system. The valve and its related components also tolerate great variations in temperatures.
6) The design of the valve will also allow it to be used to regulate the flow of any gas or liquid not corrosive to silastic.
7) The 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.

In evaluation tests, several valve units incorporated in this orthotic system have been in use by patients for six months without experiencing problems in the control system. The unusual physical characteristics of the silastic rubber tube, including inertness, corrosion resistance, and fatigue resistance, are considered to be the primary factors for its successful operation.

Other control modes including electronic and electro-mechanical devices have been developed and evaluated for particular applications and are reported elsewhere.[5 & 6]

ORTHOTIC COMPONENTS

A. *Finger Prehension Orthosis*

A basic aluminum hand orthosis with volar support is hinged together at the location of the proximal joint of the index finger with a unit stabilizing the semi-flexed phalangeal joints of the index and 2nd finger. A coil spring is incorporated in this joint for the purpose of dynamically assisting finger extension. One end of a power actuator is attached to a lever arm of the finger piece and the other is attached to the proximal part of the orthosis. The wrist is stabilized in a fixed neutral position. Upon contraction of the power actuator, the index and second fingers are moved toward the opposed stabilized thumb resulting in a chuck type prehension or pinch.

This type of powered device has been improved recently by incorporation of a friction joint at the wrist permitting passive prepositioning of the hand. This function is useful in many activities. (See Figure 8) A modified plastic hand orthosis is used to support the hand.[7] The force of the power actuator is transmitted to the finger section by a cable passing through a teflon lined coupling at the wrist joint allowing this movement to take place.

B. *Extremity Abduction Unit*

A system utilizing the vector parallelogram principle was designed to achieve the objective of abducting the extremity independently of elbow flexion. (See Figure 9)

This four-joint parallelogram system has the following functions:

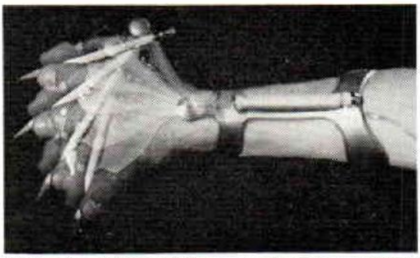
Figure 8—Powered finger prehension orthosis allowing passive prepositioning of hand.

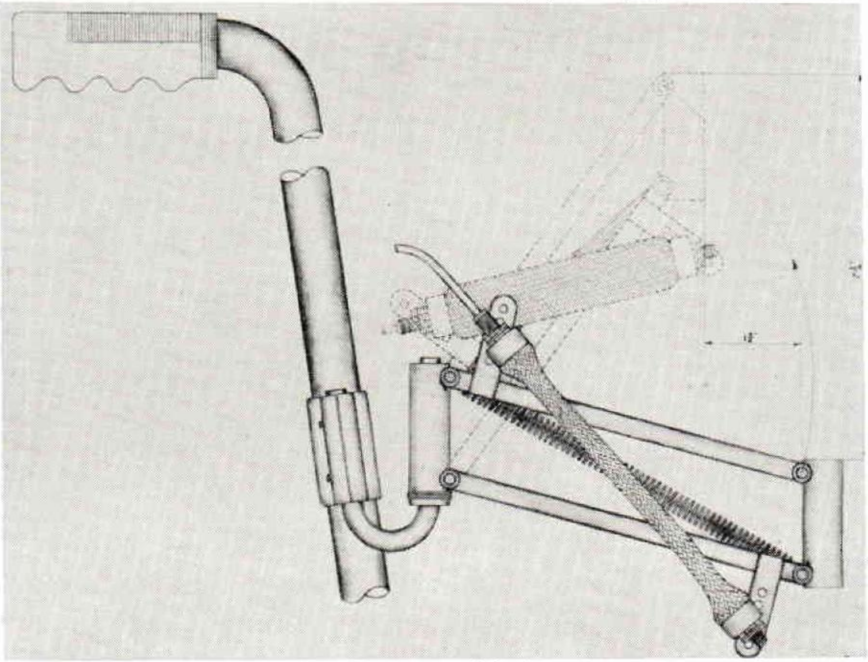
Figure 9—Extremity abduction unit.

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.

Coil springs are incorporated in the unit to counteract the force of gravity on the extremity and permit the power actuator to provide its active force to elevate the extremity. Provision is made to adjust the force and position of the coil spring and actuator in relationship to the multiple-joint axis system of the vector unit.

C. *Elbow Flexion Unit*

This device is designed to flex the elbow with its fulcrum point located on the medial side of the elbow and corresponding to the axis of the epicondyles. The unit is linked together with the abduction device by means of a swivel arm with a fulcrum point corresponding to the location of the olecranon. This permits inward and outward horizontal movements of the forearm. (See Figures 10 and 11)

A telescopic tube and rod connected to the flexion units acts as an attachment for the hand support, and also allows voluntary supination and pronation. If desired, the hand can be prepositioned and fixed there by means of a set screw. One end of the power actuator originates on the radial side of the wrist and the other is secured slightly above the fulcrum of the elbow thus bringing about elbow flexion.

In the initial tryouts it was found necessary to incorporate a spring which would initiate extension of the forearm when the elbow was fully flexed. Also, when the power actuator was deflated, the forearm needed cushioning during the last phase of extension. One coil spring located inside at the end of the telescopic unit and linked to the elbow joint, proved adequate for both functions.

The shoulder abductor and elbow flexor components are made from stainless steel. Teflon, needle thrust and roller bearings are incorporated in the joints for the purpose of producing low frictional resistance.

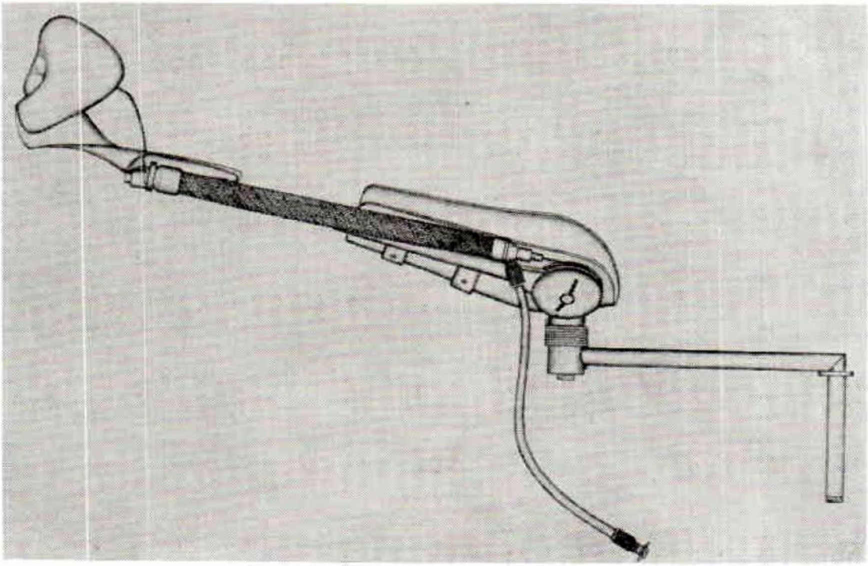

Figure 10—Elbow flexion unit.

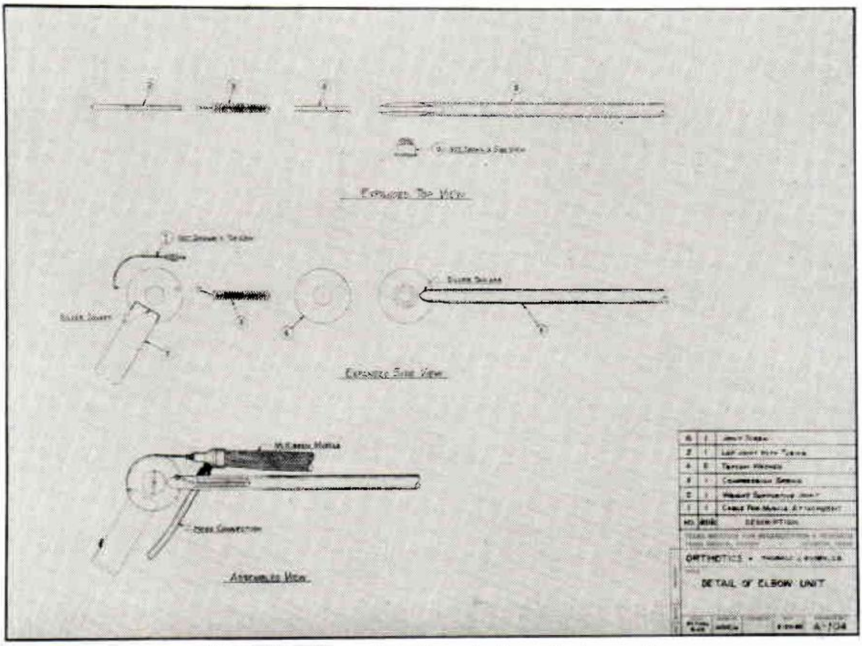

Figure 11—Expanded view of elbow flexion unit.

A moulded elbow and forearm trough made of laminated polyester resin is attached to the unit. A cutout is located at the position of the olecranon. This permits firm seating of the elbow and prevents 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 leather strap.

During the past eight months, ten powered orthotic systems have been applied on patients with various etiology. Evaluation of these including new adaptation are continuously being followed and evaluated.

CASE STUDIES OF PATIENTS

The following illustrations show three different types of orthotic applications on patients.

CASE #1: Figure 12, B. B., White, Male, Age 26.

Diagnosis: Cord lesion at C-4 and 5 level due to a trampoline accident, December 30, 1957.

This patient has almost normal function of both upper extremities with the exception of paralyzed hands.

After an evaluation for external power, application, an orthosis for the right hand was designed and applied providing index and long finger prehension against the opposed stabilized thumb. On the left side of the lapboard, a double action control unit activated by a rocker bar was mounted and controlled by the left forearm. This arrangement gave the patient a positive control site, which he learned to operate effectively in a very short time.

The CO_2 container, valve unit, and tubes were mounted on the under surface of the lapboard (see Figure 13). This permitted the patient to used the equipment while in bed, or during transportation by car, etc.

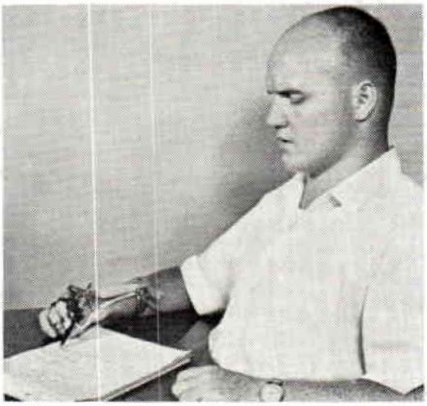

Figure 12—Powered finger prehension orthosis adapted to patient.

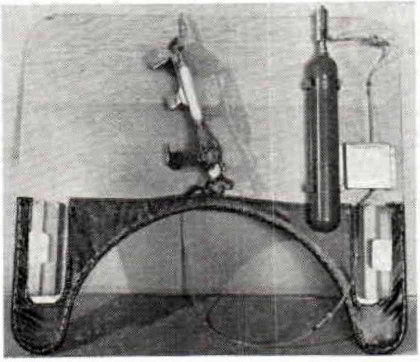

Figure 13—CO_2 container and valve box mounted on the under surface.

Before Application

1) Typing and writing with special made devices.
2) Feeding accomplished with eating utensils attached to hand orthosis.

After a short training period, the following summary from the occupational therapy report revealed the scope of his extended activities.

After Application

1) Shaving with a safety razor and handling all aspects of the activity after equipment is placed on his lapboard including shaving cream, wash rag, and after-shave lotion.
2) Feeding, including cutting thin slices of meat by using a rocking knife. Also, he can handle his drink, salt, and pepper, etc.
3) Brushing teeth (swivel). This includes handling tooth paste independently.
4) Telephone. This includes dialing.
5) Playing cards. He can handle cards with addition of card holder.
6) Typing and writing—increased in speed and tolerance.

Recently it was learned that this patient has decided to continue his education. He has been accepted at the university he attended prior to his accident. His goal is to become a patent lawyer.

CASE #2: Figure 14, L.E.P., White Female, Age 26

Diagnosis: Poliomyelitis. Onset, September 28, 1951.

This patient has minimal residual function of the right hand including radial wrist extensors, opponents of the thumb and scattered intrinsics throughout the fingers. This muscle picture enables her to grasp objects in a gross manner. Only weak wrist flexor and supination function was present in the left extremity.

Due to the total absence of function about the elbow and shoulder region in both arms, it was decided after the initial evaluation to apply power assistance to the right extremity to restore elbow flexion and shoulder abduction. The slight movement of function in the left wrist was found adequate to activate the two double control valves mounted on the left side of the lapboard. The CO_2 container was mounted on the under surface and polyvinyl tubes connect the power supply, valves, and power actuator. Snap disconnects are incorporated in the tubes so the individual components can be easily separated.

The following summary of functional activities prior to and after application was submitted by the Occupational Therapy Department.

Before Application

1) Turning pages with suspension sling applied to the right arm. This was not accomplished smoothly or with ease and required a great deal of positioning.
2) Smoking was possible if someone put cigarette in holder and positioned her arm in a flexed position.
3) Typing—minimal and could be accomplished only with right suspension sling attached.
4) Writing was restricted in range, shaky and her work tolerance very low.

After Application

1) Turning pages in a magazine, book and newspaper accomplished coordinately.
2) Smoking. Can put cigarette in holder but cannot light it safely.
3) Writing with slightly built up pencil and raised surface for as long as three hours with brief rest periods.
4) Feeding—independent with adapted fork, plate guard and lazy susan rotating disk. She is feeding herself three meals a day.
5) Makeup—can apply powder, rouge, eye makeup, and lipstick. She has a mirror that sits on her lapboard and a makeup holder for all cosmetics.
6) Typing accomplished with ease. Can insert paper, fold letter and insert in envelope.

Avocational Interests

Activities we have explored: (All these accomplished after setup.)

a. Mosiacs
b. Hook rug
d. Ceramics
e. Bongo drums
c. Leather lacing

At present this patient is consulting a vocational counselor for the possibilities of getting a job she would be capable of handling.

Figure 14—System providing elbow flexion and shoulder abduction for patient.

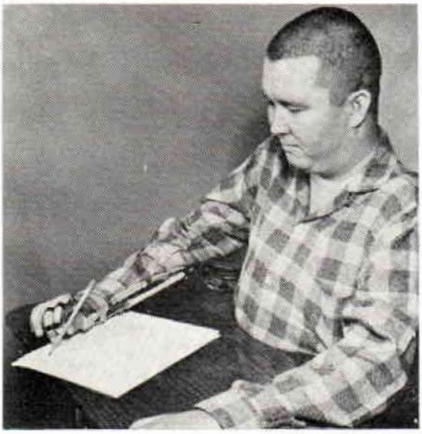

Figure 15—Complete powered system providing finger prehension—Elbow flexion—Shoulder abduction.

CASE #3: Figure 15, J.G.R., White Male, Age 27

Diagnosis: Poliomyelitis. Onset, August 28, 1956.

This patient is essentially flaccid throughout the upper extremities with the exception of trace and poor muscle movements in the shoulder girdle group. The only residual muscle function present in the lower extremities is located in the left leg, a fair + M. Peroneus longus and M. Peroneus brevis and good flexors and extensors of the foot.

Externally powered equipment providing finger prehension, elbow flexion and shoulder abduction on the right was adapted to this patient. Six valves were mounted under the left foot pedal of his wheel chair. Holes in the foot pedal exposed each control button and by a foot plate arrangement these were activated by inward and outward movements of the patient's foot.

Due to his personal business obligations, he did not receive formal training in the use of his equipment; however, upon his discharge, he was able to turn pages and use an adding machine of most importance to him as director of a book and magazine selling business. At a later date, he will be scheduled for a follow-up training program.

GENERAL CONSIDERATIONS

This system, with the exception of the powered finger prehension orthosis, cannot function without being rigidly supported by, for example, a wheel chair. Its functional success depends entirely on the precise alignment with the anatomical structure of the upper extremity.

The power actuators as used in the described orthotic system are only adequate for light functional activities.

As the application of this system increases, a detailed engineering analysis must be initiated, including stress analysis, durability and fatigue tests and many other related studies.

SUMMARY

Progress toward the development of a simplified and controllable orthotic system for restoring useful hand and arm action is described. This system, at the present time, is intended to serve practical needs of a particular class of patients, namely, those who are wheel chair bound and have marked muscular deficiency of the upper extremities. The system as a whole has been shown through practical experience with quadriplegics to restore with minimal training actions of immediate importance in daily activities, such as feeding, writing, manipulating books, attending to head and neck hygiene, and numerous others of similar nature.

Several new mechanical components which contribute to the function of this system are described also. These include a vector parallelogram elevator mechanism, a spring loaded elbow axis joint, a wrist friction joint, and a double and single action pinch-tube valve. The unique feature of this system is the manner in which these mechanical components are combined to produce synchronized and smoothly phased motions of the upper extremity segments.

Case studies on three typical patients of the type to whom this system is especially useful are given. Detailed comparisons provided by occupational therapists are included, revealing marked degrees of improvement in typical activities due to application of this orthotic system.

ACKNOWLEDGEMENT

The author expresses his appreciation to the numerous members of the medical staff at the Texas Institute for Rehabilitation and Research whose continuous encouragement stimulated progress throughout this research effort. Also, valuable contributions have been made to the development and sequential improvement of this orthotic system through the coordinated efforts of all members of the staff in the Orthotics Department.

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CLINICAL PROSTHETICS AND ORTHOTICS COURSE FOR PHYSICIANS AND THERAPISTS OFFERED BY UCLA

The University of California, Los Angeles, Prosthetics Education Program has announced a new course for physicians and therapists which will be presented in the 1963-64 academic year. The course will last two weeks, and will cover the major fields of upper and lower extremity prosthetics, upper and lower extremity orthotics, and spinal orthotics.

This new course is designed to provide a thorough refresher on the basic principles of these fields, plus new material on all of the newest techniques and devices. Those who have taken previous courses at UCLA will find ample information on all the latest advances in prosthetics, such as the total contact plastic socket, hydraulically controlled prosthetic units, the patellar tendon bearing below knee prosthesis, the new functional long leg brace, and the use of porous laminates for prosthetic sockets.

The two-week session will include an all day field trip to Rancho Los Amigos Respiratory Center for special presentations on devices for the so-called "totally disabled." Completion of the two-week course will be the equivalent of attendance at all of the courses in prosthetics and orthotics presently offered at UCLA for physicians and therapists.

This new comprehensive course has been designed and is being presented in answer to requests from the Veterans Administration, from various medical societies and from facilities of several of the nation's larger teaching institutions. Four presentations of the course are offered: October 14 to 25 and December 2 to 13, 1963, and February 10 to 21 and April 6 to 17, 1964. Inquiries concerning the courses should be addressed to: Prosthetics-Orthotics Education Program, UCLA Medical Center, Los Angeles 24, Calif.