INTRODUCTION

Man's exposure to the environment in our era of technology, coupled with the general increase in population, accounts for the yearly increase in the patient population suffering from traumatic injuries. Those patients who, as a result of injury to the cervical spinal cord, have become quadriplegic, represent the greatest challenge in rehabilitation. In the period from 1957 to 1965 an increase from 5.6 to 8.1 per thousand population of patients with complete or partial paralysis has been noted (1). Fortunately, quadriplegic patients represent only 2.3 per cent of this total. For these, however, with the exception of lower level quadriplegics (C 7–8), there is rarely any medical-surgical procedure which would at least provide the higher level quadriplegic with useful hand and arm functions. It is for this group of patients, i.e., the high-level quadriplegic, that the fields of orthotics and bioengineering may offer some hope in restoring volitional control of hand and arm functions.

Much of the design of hand and arm orthoses represents a carry-over from times when poliomyelitis was prevalent. An example of this is the balanced forearm orthosis developed at Warm Springs, Georgia (2). A number of externally powered orthoses include the principle of the balanced forearm orthosis as an integral part of their design, including the electric arm orthosis to be described in this paper (3, 4).

While the low-level quadriplegic patient (C 7–8) very rarely is in need of orthotic devices to provide useful hand function because of adequate residual, though not normal, hand function, the other three levels of quadriplegic patients do require orthotic devices. This may be as simple as a wrist-driven prehension orthosis for the C 6–7 quadriplegic, an electrically driven prehension orthosis for the C 5–6 level, or may be so complex as to require motorized shoulder, elbow, pronation-supination motion in addition to prehension. The purpose of this paper is to
describe some of the design considerations for the C 4–5 quadriplegic
patient in restoring useful hand and arm functions.

The orthosis should be as simple a mechanism as possible, and should
be unobtrusive and reliable both mechanically and, most importantly, in
its method of control. Obviously, at the present state of the art it is im-
possible to hope to restore normal hand and arm functions, particularly
if one considers the intricacy of hand function alone. But there is hope
that such an arm orthosis would at least provide the patient with the
most important functions of activities of daily living, and possibly aid in
certain vocational pursuits. These considerations were implemented in
various models of the electric arm orthosis developed at the Institute of
Rehabilitation Medicine, New York University Medical Center (Fig. 1).

The high-level quadriplegic, for whom the powered arm orthosis is
indicated, is wheelchair-bound. The design of this orthosis, therefore,
must not only be compatible with the anatomy of the extremity it is fit-
ted to, but also must be compatible with the wheelchair. The wheelchair
serves as an excellent frame to which the arm orthosis can be mechan-
ically connected. One of the aims in the design of the powered arm
orthosis was to eventually make it available to the broadest possible
patient population for whom such a device is indicated. As such, we
attempted to use commercially available components wherever possible
so that repair, maintenance, and replacement could be performed by
individuals other than a highly trained orthotist or a specially trained
engineer. An adjustable ball-bearing bracket used with the conventional
balanced forearm orthosis serves as the connecting link between the
powered arm orthosis and the wheelchair. It serves at the same time as a
pivot in the three-pivot linkage system supporting the arm (Fig. 2).

SHOULDER MOTION

Since the IRM Electric Arm Orthosis does not include a mechanical
shoulder joint, the three-pivot linkage system serves to provide horizontal
abduction and adduction, which need not be motorized. This is possible
by a combination of factors. First, by supporting the extremity on the
three-pivot ball-bearing linkage system, the effects of gravity are nearly
eliminated. Note that the arm is supported in a forearm trough which is
attached to the distal swivel arm near the distal pivot (Fig. 3). Second,
residual shoulder girdle motion can now be usefully employed to initiate
horizontal abduction or adduction. Such residual motion will not be ob-
tained unless, as stated, the effects of gravity are nearly eliminated in the
linkage system. Changes in the angulation of the pivot axes, with regard
to the vertical, may be used as a bias to induce motion in one or more
directions. The degree and direction of angulation from the vertical of
the pivot axes depend on proper evaluation of the patient's residual
FIGURE 1.—The IRM Electric Arm Orthosis.

FIGURE 2.—A three-pivot linkage system supports the patient’s arm.

FIGURE 3.—The forearm trough is attached to the distal swivel arm.
motor power in the shoulder girdle and, of course, on the skill of the orthotist to achieve the optimum range of horizontal abduction or adduction. Other shoulder motions must be motorized. These are: shoulder flexion-extension and abduction-adduction. For this purpose a ball-bearing parallelogram is used, which at the same time serves as the proximal swivel arm (Fig. 2). Activation of the parallelogram by means of a Bowden cable attached to the distal vertical bar results in vertical elevation of the entire orthotic arm system. If the arm has been positioned in horizontal adduction by the patient then this motion can be effectively looked upon as shoulder flexion (Fig. 4). If, however, the arm is in horizontal abduction then activation of the parallelogram results in shoulder abduction (Fig. 5). In other words, the patient can pre-determine whether shoulder flexion or abduction is initiated when the parallelogram is activated by pre-positioning his arm in horizontal adduction or abduction. The parallelogram consists of two 2½ in. vertical ball-bearing aluminum bars and two 6-in.-length aluminum bars connecting the two vertical bars. An adjustable ball-bearing pivot is attached to the distal vertical bar which serves as the middle pivot in the three-pivot linkage system. The distal swivel arm runs from there to the forearm trough (Fig. 2).

ELBOW MOTION

The elbow unit is an integral part of the distal pivot. It consists of an “L-shaped” bracket and ¾ in. stainless-steel rod fitting into the distal swivel arm at one end, and a 2½-in.-dia. aluminum pulley on the prox-
imal arm of the “L.” The shape and dimension of the “L” must be such that the axis of the pulley coincides with the patient’s anatomical elbow axis, i.e., at the apex of the medial humeral epicondyle. The pulley is driven by a looped Bowden cable which flexes or extends the elbow (Fig. 6).

**PRONATION AND SUPINATION**

The forearm trough which is fastened to the elbow flexion pulley extends approximately 1½ in., proximal to the olecranon, thus supporting the humerus when the elbow is flexed. Distally, the trough is fitted loosely around the forearm to permit pronation and supination. This distal looseness of the trough is necessary to permit nearly unrestricted pronation-supination range to accommodate for the incongruency between mechanical and anatomical pronation-supination axes, since the mechanical axis is located lateral to the patient’s ulna (Fig. 7). A looped Bowden cable drives a 1½-in. pulley at the proximal end of the pronation-supination shaft. The distal end of the pronation-supination shaft forms the proximal portion of the wrist joint which is friction-controlled, thus adding another, passive degree of freedom (Fig. 8). The patient may use his chin to preset the wrist angle for various activities.

**FINGER PREHENSION**

The hand portion of the orthosis is attached to the wrist joint described above. It supports the arch of the hand from the volar aspect and includes a thumb post opposing it to the index and middle fingers. Finger prehension is provided by powering the metacarpophalangeal (MP) joints of the index and middle fingers. A Bowden cable is attached to
The friction-controlled wrist unit permits passive wrist flexion and extension. An outrigger on the volar aspect of the MP joint for this purpose, while a tension spring attached to a dorsal outrigger provides finger opening. The interphalangeal (IP) joints of these fingers are immobilized to provide for a three-point jaw-chuck type of pinch (Fig. 9).

**ACTUATORS**

All actuators for the electric arm orthosis are remotely located in back of the wheelchair (Fig. 10). Power transmission from the actuators to the orthotic arm segments is accomplished by means of Bowden cables. There

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**SUPINATION**

A looped pulley system, thus supporting the forearm and supination. This distal pulley is attached to the pronation-supination unit and is located on the volar aspect of the MP joint. The interphalangeal (IP) joints of these fingers are immobilized to provide for a three-point jaw-chuck type of pinch (Fig. 9).
are several advantages to this arrangement. First, mechanically it is less complex than direct drives at individual joints. Second, the arm orthosis itself is much lighter and less obtrusive. This, of course, has important psychological implications in that the appearance is less robot-like, since the actuators are not within the patient's visual field, and certainly his appearance to others is psychologically important as well. Third, the power requirements are reduced in this system since the motors need to drive only the respective orthotic and anatomical segments, rather than these segments plus distally located motors as in a direct drive system. Thus, the overall system is more efficient.

In our initial attempts to construct this orthosis, we placed emphasis on actuators which were readily commercially available and were inexpensive. For shoulder actuation, an automobile window lift motor was
modified by changing its gear ratio to achieve a slower speed of 15 revolutions per minute and increasing the torque to 49 in.-lb. This motor is used to elevate the parallelogram. A coil spring counteracts the force of gravity to provide nearly uniform speed in both directions. Lowering the parallelogram is simply achieved by reversing the motor and allowing gravity to lower the arm. A 1-in.-dia. aluminum pulley on top of the gear reduction unit drives the Bowden cable for active elevation of the parallelogram. Limit switches were installed to prevent harmful, excessive

Figure 12.—Finger actuator with exploded view of slip clutch.
excursion. The same type of motor and modification was used for elbow motion. However, power transmission from the motor to the elbow unit is by means of a double cable, to not only actively flex the elbow but to actively extend it as well.

Because the torque requirements for pronation-supination are considerably less than for either shoulder or elbow motion, a small permanent magnet motor was used. This motor has an operating torque of 145 in.-oz. and a speed of 35 to 40 r.p.m. A 3-in.-dia. gear placed eccentrically to the shaft of the motor serves to reduce the speed and to provide an attachment point for the Bowden cable (Fig. 11). For finger flexion a motor with the same specifications was used. It was adapted with a slip clutch with a 1-in.-dia. pulley to permit adjustability of the prehension force and to act as a safety device to prevent excessive and harmful pressures on the finger and thumb pads in case of switch failure (Fig. 12).

POWER SOURCE

The patient for whom the electric arm orthosis is indicated also requires an electrically driven wheelchair. Such wheelchairs ordinarily use two 6-volt batteries as their power source. This same power source can, therefore, be used for the 12-volt power actuators of the electric arm orthosis, since the two 6-volt batteries are connected in series when the chair is switched to the high speed mode.

![Figure 13.—The contralateral extremity controls the powered arm orthosis.](image)
Lehneis and Wilson, Jr.: Electric Arm Orthosis

CONTROL MODE

The contralateral extremity, supported in a three-pivot linkage system, is utilized to control the powered arm (Fig. 13). Horizontal motion of this system can be induced by residual arm or shoulder motion in combination with head motion. The distal extension of the forearm trough terminates in a hollow hemisphere which fits over the spherical extension of the joy-stick control, producing a ball and socket connection. Four sets of switches placed at right angles to each other control...
each of the powered motions; i.e., shoulder, elbow, pronation-supination, and finger flexion may be activated by displacement of the joy stick in a given direction. Any two motions can be synchronized by activating two switch sets simultaneously. Subminiature microswitches (3 oz. maximum operating force, 7 amp. capacity) were chosen for these switch sets because of the limited force and excursion the patient has available. The switch sets are arranged double-pole double-throw to produce a sequential control mode (Fig. 14 and 15). This is an important feature of the control system because it permits unidirectional control of one degree of freedom; i.e., depending on the degree of unidirectional displacement of the joy stick, a given motion may be controlled in the forward or reverse direction. For example, a small displacement of the switch set controlling the shoulder motion will result in elevation-abduction, while a large displacement will reverse polarity of the actuator and lower and adduct the shoulder. All other motions are controlled in the same fashion, that is, the first sequence results in an active motion, i.e., elbow flexion, supination, and finger flexion, while the second sequence causes a reversal of direction. Because of the high-current draw of the window lift motors used for shoulder and elbow motions, relays were needed in conjunction with the low-current rating of the microswitches (Fig. 16).

A four-pole toggle switch medial to the joy-stick control is used as an on/off control for the orthosis and for high/low speed control for the
shoulder, elbow, pronation-supination, and displacement of the joy stick in a synchronized manner. This is achieved by activating two microswitches (3 oz maximum weight) which are controlled by the patient's head and shoulder motions. When the joy stick is moved, the forearm trough moves with it, allowing the arm orthosis to be placed over this four-pole toggle switch when needed. Wheelchair propulsion is controlled with the powered arm orthosis when placed over the joy stick on the control box for the wheelchair.

**RECENT DESIGN MODIFICATIONS**

Although the overall function of the orthosis has remained unchanged, a number of important design modifications were made to refine and simplify the system. The actuators and the electrical system were simplified by calculating the forces and speed requirements for elbow and shoulder function in order to utilize appropriate permanent magnet motors, thus eliminating the need for relays. This reduced considerably the size of the actuator pack (Fig. 17 and 18). All other modifications were confined to the elbow and pronation-supination units.

The first modification of the elbow unit consisted of replacement of the circular pulley with two semi-circular pulleys to minimize the bulk in that area. The Bowden cable from the elbow actuator was attached to one of the pulleys while a second Bowden cable was attached to the second pulley connecting it to a tension spring which serves as an
FIGURE 17.—Permanent magnet motors with limit switches and slip clutch (right).

FIGURE 18.—Reduced size actuator pack in back of the wheelchair.

FIGURE 19.—Modified elbow unit with flexion assist.
elbow-flexion assist to reduce the load on the motor and thus approach a more nearly uniform speed in flexion and extension (Fig. 19). The first patient fitted with this orthosis became gainfully employed as a disc jockey, after a period of training in the use of the orthosis. As a result of his experience following approximately 18 months of wear, additional modifications were made to the elbow unit.

In his vocational environment, as well as in activities of daily living, the patient found the constant elbow flexion speed his greatest limitation in the use of the orthosis. It was, therefore, modified to provide him with proportional speed control. Two 12.5-watt, 25-ohm rheostats were arranged in a control lever assembly medial to the original control box with a set of subminiature microswitches (Fig. 20 and 21). A new permanent magnet motor with an operating torque of 530 in.-oz. and a speed of 11.5 r.p.m. was installed, with a 1-in.-cable pulley providing 62.5 in.-lb. of force. The proportional speed varies from 11.5 r.p.m. (or approximately 2.5 seconds) for full elbow flexion through a range of 120 deg. to 6 r.p.m. (or approximately 5 seconds). Torque at maximum speed is 85.7 in.-lb., and 43.75 in.-lb. at minimum speed. The mechanical assembly of the elbow unit itself was not changed. The patient found this arrangement far superior to the constant speed in minimizing or nearly eliminating overshooting of the target while flexing or extending the elbow. Other important modifications of the orthosis were concerned with the pronation-supination assembly.
Figure 21.—Proportional speed control lever medial to the joy stick.

Figure 22.—Modified pronation-supination unit permits conversion of a linear pull to forearm rotation.

Figure 23.—Diagram of modified pronation-supination unit.
Lehneis and Wilson, Jr.: Electric Arm Orthosis

The first design change was the elimination of the bulk posterior to the elbow produced by the pronation-supination pulley. The steel rod connecting the hand portion of the orthosis to the trough terminates in a spiral helix which fits in a sliding nylon sleeve which is contained in a steel tubing attached to the trough. This design permits a linear pull on the sliding sleeve to be converted to rotation of the steel rod, i.e., supination. A return spring serves to pronate the unit as the motor is reversed (Fig. 22 and 23). While this modification serves the purpose it was designed for, i.e., reducing the bulk of the orthosis, it did not solve some of the functional problems experienced by the patient. This problem was chiefly the result of the axis of rotation of the mechanical unit being eccentrically located to the center of the arm. This caused any object held in the hand to describe an arc as the patient supinates or pronates his forearm. To overcome this problem, two semi-circular aluminum tracks were fitted to the forearm trough. Nylon blocks, to which the wrist unit and hand piece were fastened, travel on these tracks for supination or pronation. Thus, the axis of rotation of the hand unit lies within the forearm center and closely resembles the anatomical axis of pronation-supination (Fig. 24).

Figure 22.—Modified pronation-supination unit permits conversion of a linear pull to forearm rotation.

Figure 24.—Semicircular tracks provide for mechanical and anatomical approximation of congruency of pronation-supination axis.
SUMMARY AND CONCLUSION

An electric arm orthosis is described, which aids the severely disabled quadriplegic patient at the level of C4-5 to perform certain activities of daily living. One case discusses how a patient pursues a vocational objective. The mechanical design of this orthosis is such as to permit the patient maximum residual non-motorized function. This is possible by nearly eliminating the effects of gravity in a finely balanced three-pivot linkage system. Every attempt was made to minimize the amount of hardware attached to the patient's extremity by remote location of the actuators and the power source. It is felt that the psychological implication of this and permitting maximum residual motion may create greater patient acceptance as compared to a totally powered arm with direct drives. While the mechanical design of this orthosis appears to be adequate, control problems remain. Attempts have been made to reduce these by using sequential switches and proportional control, at least for elbow motion. But reliable control and avoidance of inadvertent operation are yet to be achieved. Future developments must be primarily concerned with solving these problems. Proportional control of all motorized joints and hybridization of myoelectric and biomechanical control may possibly provide the answer. It is, however, unlikely that the problem of sensory feedback will be solved in the near future. While improvements are continuing to be made in the design of externally powered arm orthoses, they cannot yet be considered routine clinical devices. They may aid in certain aspects of activities of daily living and can, in selected instances, help in vocational rehabilitation.

REFERENCES