TREATMENT OF THE HEMIPLEGIC UPPER EXTREMITY USING ELECTRICAL STIMULATION AND BIOFEEDBACK TRAINING*

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INTRODUCTION

The combination of positional feedback of joint motion and electrical stimulation of paretic musculature previously has been demonstrated to enhance joint motion in hemiparetic patients who have poor voluntary motor control.[1] In this type of automated treatment, audio and visual displays proportional to joint position are supplied to a patient as: 1) a sensitive and immediate sensory feedback of his joint motion; 2) a means of comparing his joint position with established goals for motion; and 3) positive reinforcement of goal attainment. Electrical stimulation of paretic musculature to complete the full joint range provides neuromuscular facilitation of a patient's voluntary effort. A comprehensive treatment program for the hemiparetic upper extremity using electrical stimulation and biofeedback was designed, and individual treatments and devices previously demonstrated to be singularly effective were combined in an integrated program of automated therapies. The purpose of this paper is to describe the treatment program and therapeutic rationale.

BACKGROUND

Rehabilitation of motor function usually involves three central goals:

1. Maintaining strength of strong muscles or increasing strength of muscles weak from disuse.
2. Maintaining or increasing passive or voluntary active ranges of motion impaired as the result of spasticity in paresis or disuse.
3. Improving motor control by sensorimotor re-education in muscles demonstrating patterned or weak selective voluntary control.

Both neuromuscular electrical stimulation and various forms of biofeedback have been shown to be effective in achieving these goals.

Electrical Stimulation

Neuromuscular electrical stimulation has been widely used to restore function in the lower extremity of the hemiparetic stroke patient. Many stimulators have been developed to trigger foot

dorsiflexion during the swing phase of gait by direct stimulation of the peroneal nerve or by stimulation over motor points of the pre-tibial muscles.[2-8] In addition to an immediate motor response, a facilitation of voluntary ankle dorsiflexion following the stimulation period has been observed in some cases.[8-10] Electrical stimulation treatment also has been reported to result in functional gains at unusually late times in the recovery period, even after other forms of therapy have proven inadequate.[6,11,12] In addition to single-channel stimulation of the peroneal nerve, multi-channel stimulators have been developed to correct the complex gait disorders of hemiparetic patients by augmenting contraction of hip and knee, as well as ankle musculature.[13-15]

Improved volitional strength and active motion of paretic limbs have been noted following electrical stimulation, in addition to neuromotor facilitation and re-education.[3,4,6,16,17] Correction of joint contractures[22,31,54] and reduction of antagonistic muscle spasticity[3,6,9-11,18-22] also have been effected by electrical stimulation treatment.

Compared to its application in the lower extremity, electrical stimulation has been used less frequently to treat anomalies of the upper limb. At least in part this is due to the complex nature of the upper extremity. Hand function requires the control and coordination of a large number of individual, small muscle groups. For many hand and arm activities speed and accuracy are more important than large amounts of muscle force. Nevertheless, neuromuscular electrical stimulation has been reported by some investigators to be an effective clinical therapy for the restoration of upper limb function following neurological dysfunction.[23-30] Previous work at Rancho Los Amigos Hospital has shown that functional hand opening can be achieved by electrical stimulation in hemiparetic patients who have intact grasp but who lack the ability to extend the fingers or thumb. Myoelectric signals as well as joint motion caused by muscles under limited volitional control have been used to trigger the stimulation.[28-30] Passive cyclical electrical stimulation also has been shown to improve hand function by increasing voluntary wrist and finger extension strength and by decreasing hypertonia of the antagonistic flexor muscles.[22-31]

Biofeedback

Various forms of biofeedback have been extensively used in programs of motor function rehabilitation. The most common form of biofeedback used to treat patients with neurological disorders has been electromyography (EMG). Improvement in voluntary motor function (usually correction of footdrop) has been widely reported to follow EMG biofeedback treatment, even when treatment was not given until unusually late times in the recovery period.[32-36] Follow-up testing of patients who received such treatment indicated that progress made during the program was maintained.[36] Reduced spasticity has been noted by some investigators to accompany EMG feedback treatment, and in some cases the primary

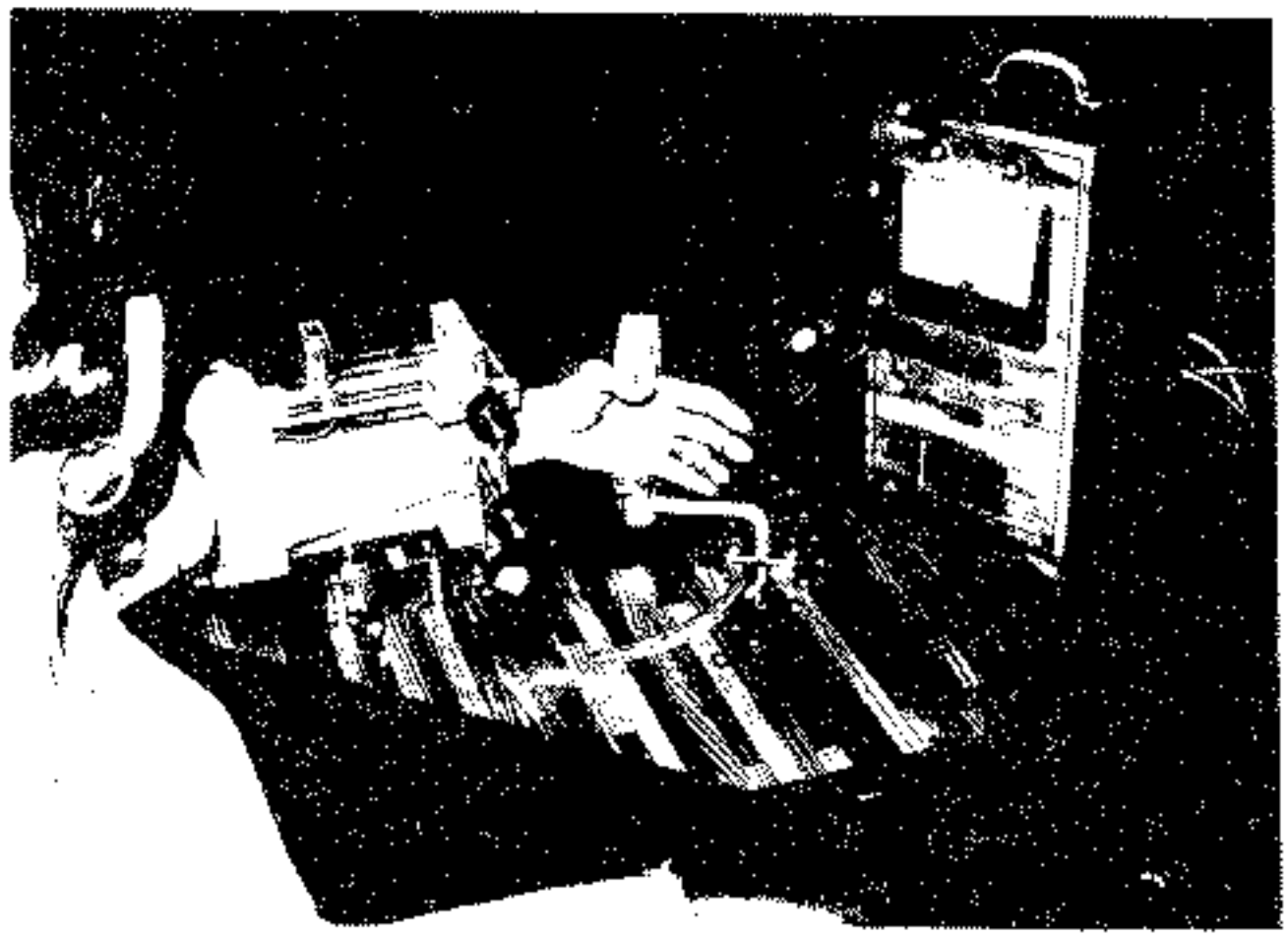

FIGURE 1. Positional feedback stimulation training at the wrist. Wrist is stabilized in orthosis mounted to table top. Potentiometer mounted in table senses joint angle to provide motion feedback. Weights may be added to cable beneath table to provide resisted exercise. Display unit gives feedback of exercise effort by lights, audio tone, analog meter and digital display of actual joint angle. Electrical stimulation of wrist extensors is given to complete joint motion after patient achieves threshold angle by voluntary effort.

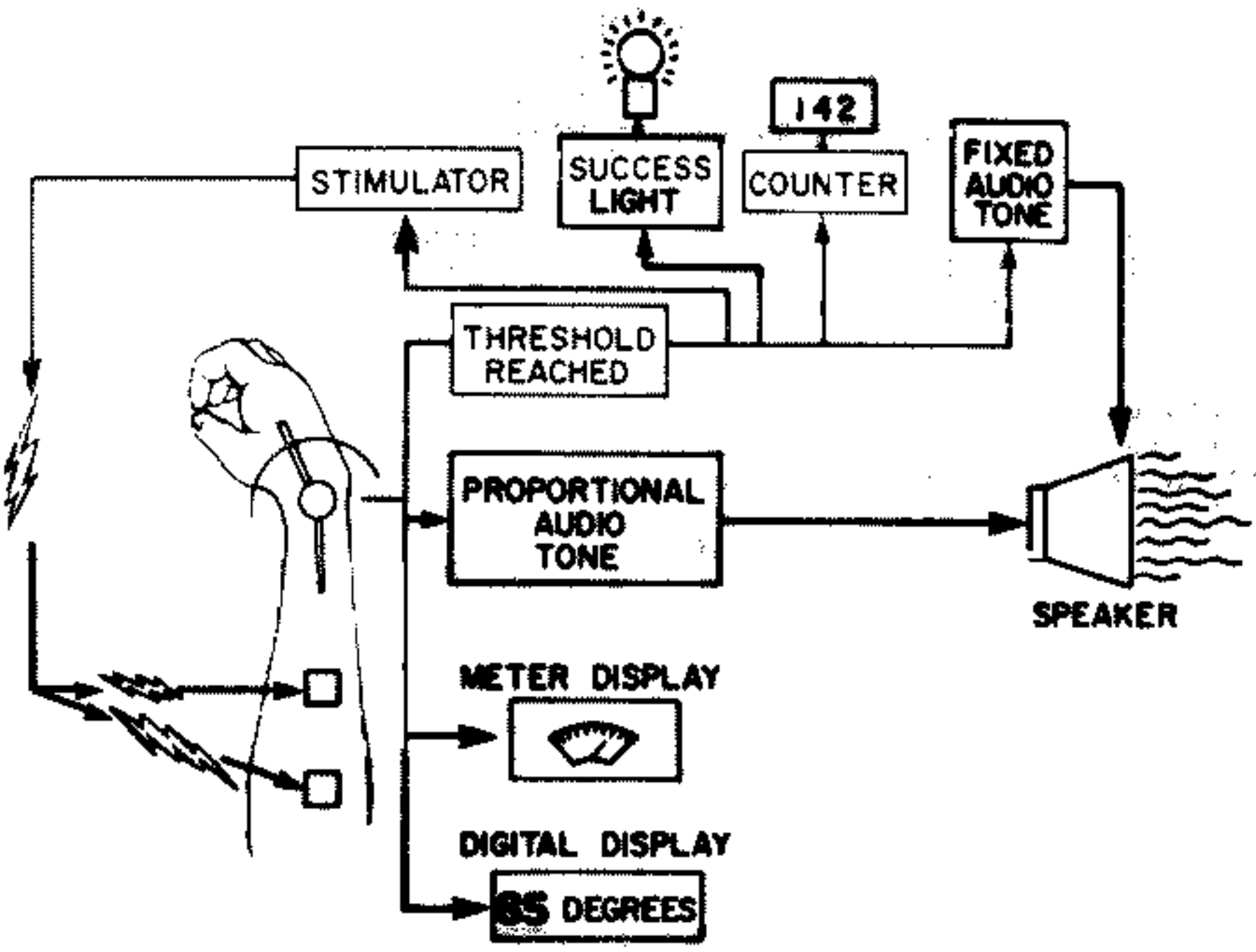

FIGURE 2. Flow diagram of positional feedback display. As the wrist is extended, a meter is deflected; a display shows joint angle in degrees, and an audiotone increases in pitch. When a goal angle is reached, a "success" light is illuminated; a counter increments; the audiotone becomes interrupted; and electrical stimulation of the wrist and finger extensor muscles is provided to complete the extension motion.

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improvement in selective wrist extension of approximately 200%, while patients receiving standard therapy increased only 50%. Although large increases in volitional motor ability were demonstrated by the patient group treated in the automated therapy program, little direct therapist time was required to administer the treatment.

RATIONALE

Various forms of neuromuscular electrical stimulation and biofeedback therapy have been developed and shown to be effective in rehabilitating motor function impaired as a result of neurological dysfunction. The most effective and efficient therapy program would seem to be one which combined elements of both techniques into a single, automated treatment providing biofeedback to facilitate a patient's existing volitional response and electrical stimulation to further facilitate and/or directly elicit a strong contraction in muscles with limited volitional control. This combination would allow a treatment to be precisely matched to a patient's changing motor abilities. Treatment could be made applicable to a wide range of patients, including both those with severe involvement and little voluntary control as well as patients with less dysfunction who primarily needed to increase existing strength and refine their motor control. Finally, an automated treatment would not have the costly and labor intensive requirement of continuous and direct therapist supervision.

Two treatment methods based on this philosophy have been clinically tested and demonstrated to be superior to conventional therapies at Rancho Los Amigos Hospital. Passive cyclical electrical stimulation has been shown to increase strength and range of motion in the hemiplegic wrist.[53] Feedback stimulation training also has been shown to increase strength and active range of motion in both synergistically patterned as well as selectively controlled movements of the hemiplegic wrist and elbow.[29]

Therefore therapy programs incorporating similar techniques of electrical stimulation and joint motion feedback that have been shown to be successful at the wrist and elbow can be utilized to treat the fingers and shoulder of the hemiparetic patient. In addition, treatment providing positive reinforcement of motion at a target joint and negative reinforcement of simultaneous motion at other joints was proposed to improve a patient's ability to selectively control movement. To enhance control of voluntary, reciprocating motion in flexion and extension, development of an automated tracking device providing biofeedback of joint motion was proposed. To train all joints of the upper extremity in the integrated control necessary for whole limb function, development of a positional placement device was proposed.

The individual treatments comprising the program are organized in a multi-level therapy program designed to provide comprehensive, contiguous treatment for the upper extremity of the hemiparetic patient throughout the patient's recovery period and appropriately graded to his changing motor abilities. Equipment was designed to be usable not only for treatment but also for quantifiable testing. In addition, equipment was made as simple as possible, to allow the general therapy staff to operate it with minimal specialized training; it also was automated, to require a minimum of therapist time.

The overall concept behind the comprehensive program was to implement engineering technology with clinical therapy to provide treatment programs which were more consistent, easier to use, more objective in recording a patient's progress, and which would result in at least equaling standard treatment results or actually increasing a patient's level of function while requiring less direct therapist time and fewer days of hospitalization

METHODS

The individual treatments comprising the multi-level program included: 1) single or multi-channel cyclical electrical stimulation for patients with little or no voluntary motor control; 2) positional feedback stimulation training of the elbow or wrist, incorporating auditory and visual feedback of joint motion with electrical stimulation for patients with a minimum of five degrees of voluntary control at the target joint; 3) selectivity training, concentrating on single joint motion without involvement of other joints for patients with 10-15 degrees of selective motion at the elbow, wrist or fingers; 4) tracking training, to facilitate rapid reciprocating motion for patients with moderate selective control of the elbow, wrist or fingers; 5) orthotic stimulation training, using an electrical hand orthosis, for patients with gross grasp but poor release due to weak finger extensors; and 6) positional placement training, to facilitate patients in learning controlled movement of their entire hemiparetic upper extremity in space.

Cyclical Stimulation

Equipment:

Three-channel electrical stimulators were built (Fig. 3) with the following parameters: 1) current amplitude -- 0-60 milliamperes with a resistance of 1000 ohms; 2) pulse duration -- 300 microseconds; 3) stimulus frequency -- 30 pulses per second; and 4) waveform -- constant current, capacitance coupled, monophasic, square waves. The period of stimulation is controlled by a single ON time, adjustable from 0-10 seconds, but each of the three channels features an individual amplitude control. A channel can be set in a mode of either "flexion" or "extension," which operate ten seconds out of phase with each other. This feature allows all channels to be set to cycle

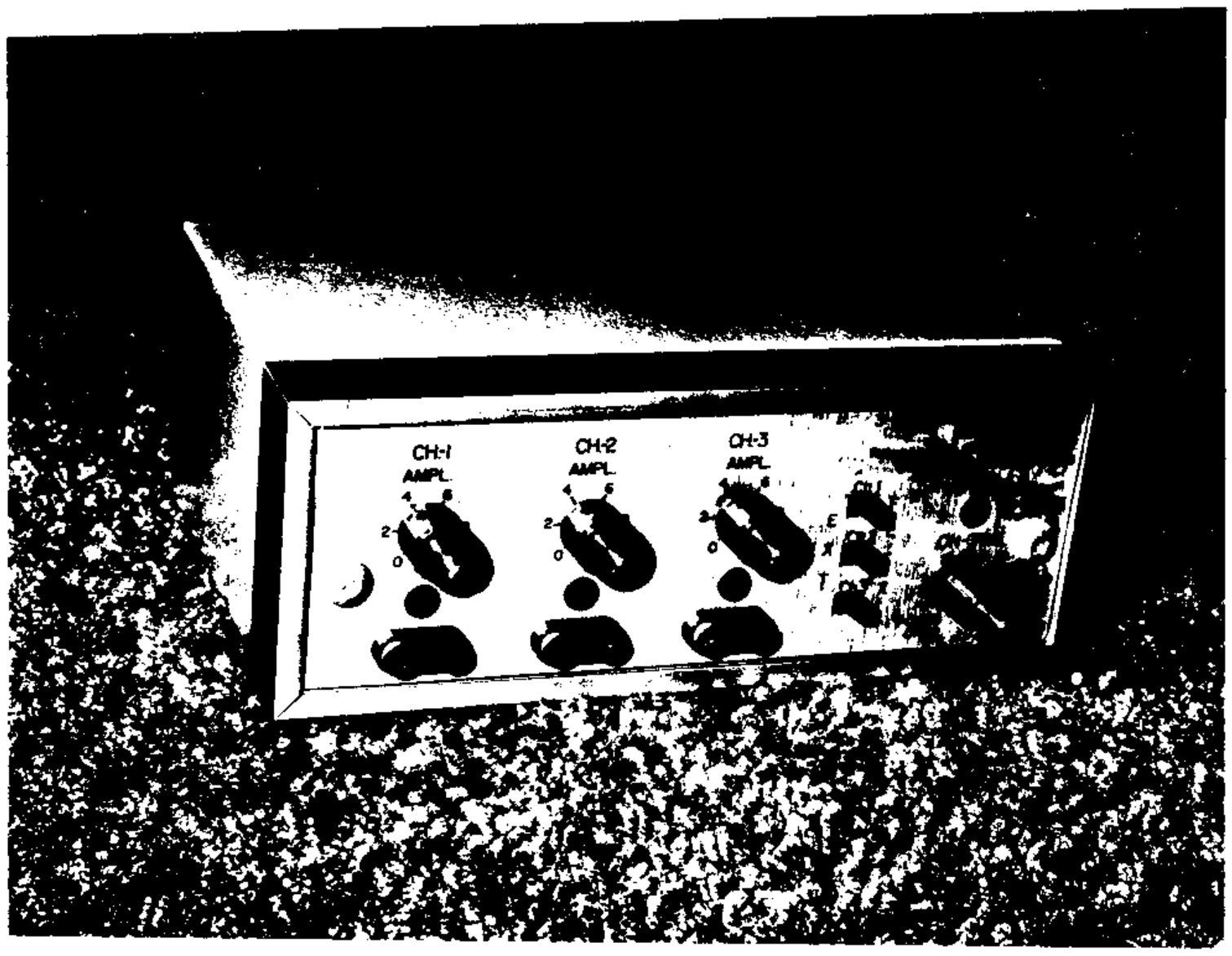

FIGURE 3. Three-channel cyclical electrical stimulator. A single duration control is used to adjust ON time of all three channels from 0-10 seconds, but each channel can be individually adjusted in amplitude. Every 10 seconds the stimulator switches between a flexion and an extension mode. Each channel may be set in either mode of operation.

synchronously; or a combination of channels may be set to alternate, thus inducing joint extension followed sequentially by joint flexion.

Clinical Program:

The lowest level of treatment in the integrated, multi-treatment program consists of cyclical electrical stimulation of upper extremity muscle groups demonstrating clinically significant weakness, lack of voluntary control, or decreased sensory awareness. Either single or multiple channel stimulation are utilized as appropriate. The antagonists of spastic muscle groups also are passively stimulated to reduce hypertonia of the latter muscles.

[30,53]

Single-channel cyclical stimulators are used to treat individual muscle groups. In general stimulation is applied for 15 minutes twice daily and was increased in intensity and duration of treatment to tolerance over 5-10 days to one hour of stimulation twice daily.

When cyclical stimulation therapy is appropriate for multiple muscle groups, one or more three-channel stimulators are used. Typical combinations of stimulation patterns provided humeral elevation, with synchronous elbow and wrist/finger extension, or elbow and wrist/finger extension followed by wrist flexion. Cyclical stimulation treatment (either single or multi-channel) was continued until discharge or until a patient advanced to higher levels of treatment.

Positional Feedback Stimulation Training

Equipment:

Due to the complexity involved in adjusting nine feedback display controls on the prototypal positional feedback stimulation trainer,[29,30] clinical use of the unit had been restricted to a few, specially trained therapists. A simplified design was constructed. The simplified units provide the same feedback information to a patient as the prototype unit, but they can be used by the general therapy staff following only minimal instruction (Fig. 4). The following modifications of the original design were made: 1) a single zero adjustment for audio tone, meter position and digital goniometer, condensing three previously necessary steps into one; 2) a momentary switch to adjust stimulation threshold, avoiding the common error of continuously reading the threshold value instead of the changing joint position; 3) a four position, rotary switch adjustment of predetermined stimulation ON times; and 4) a two position rest period switch. Thus the system previously requiring adjustment of nine controls was reduced to a unit with three variable range controls and two discrete switch adjustments.

Clinical Program:

FIGURE 4. Positional feedback stimulation training of the elbow. A simplified design of the display unit made the device easier to adjust and operate, with no compromise in the multiple feedbacks of exercise effort provided the patient.

When a patient demonstrates at least five degrees of active motion at either the elbow or the wrist, positional feedback stimulation training was begun. Training is performed using isotonic load exercise tables with adjustable orthoses to position joints adjacent to the target joint. Auditory feedback is provided by a tone which increases in pitch as joint motion increased. Visual feedback of the instantaneous joint angle is provided by a meter and a digital display. Electrical stimulation of either the wrist or elbow extensor muscles was triggered by an adjustable goal threshold detector set to a point near the patient's maximum voluntary ability to extend the joint. As a patient exceeds threshold during an exercise effort, a counter incremented and a light on the display box is illuminated, indicating successful attainment of the motion goal. Treatment is given in a 30-minute session, one to three times per day during the five day treatment week.

Tracking Training

Equipment:

A feedback tracking trainer was designed and built to facilitate reciprocating motion and selective motor control of the elbow, wrist and fingers. Two light bar displays, each composed of sequentially activated 64 LED displays, are featured on a screen on the automated device (Fig. 5). The upper light bar represents a target traveling randomly across the screen in a horizontal direction. The width, maximum excursion and rate of change of position of the tracking band are adjustable. The lower light bar represents the effort of a patient who seeks to track the target band by reciprocating flexion and extension of his elbow, wrist or index finger. An electrogoniometer, interfaced to the display unit, is worn by the patient to monitor motion at the target joint. As long as the patient maintains the display of his joint position within the tracking band, "correct" time accrues on a digital clock. When the patient exceeds the tracking band an audio tone is emitted by the device. A second clock displays the total treatment period.

Clinical Program:

Hemiparetic patients who demonstrate more than 30 degrees of selective extension of the elbow, wrist or index finger exercise with the feedback tracking trainer. The purpose of this treatment is to facilitate control of reciprocating motion and fine movements required for upper extremity dexterity. Because of the intense concentration and active participation required in this treatment, training sessions generally are given once or twice a day during the treatment week for 15 minutes or less. Treatment sessions are broken into short, 2-3 minute periods of actual tracking effort, separated by 3-5 minute rest periods.

Electrical Hand Orthosis

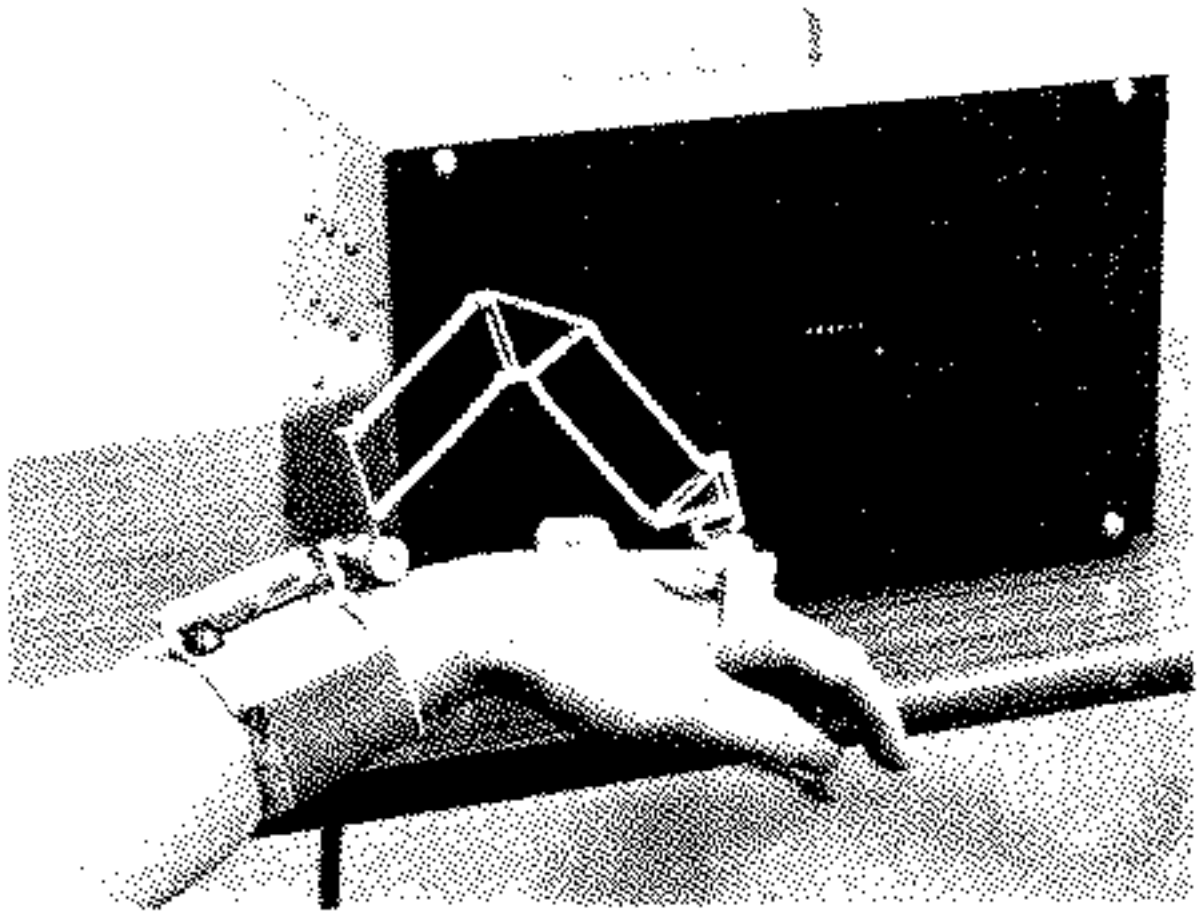

FIGURE 5. Tracking trainer. The patient must control his joint angle to follow the motion of a band of light which moves randomly back and forth across the display (upper light band). The joint position, monitored by the electrogoniometer worn by the patient, is indicated by a smaller band of light just below the target band.

Equipment:

Two hand orthoses, one controlled by the wearer's electromyographic (EMG) signals and another controlled by a minimal amount of wrist joint motion, were determined in preliminary investigations[29,30] to offer the most favorable prospects for use by hemiparetic patients demonstrating inadequate grasp and release for hand function. It was evident from those studies, however, that both prototypal orthoses required modifications in design to make them efficient and practical. During the granting period described in this report several of these modifications were made.

The EMG activated orthosis was redesigned electronically to give greater sensitivity and to filter noise (Fig. 6). Fabrication of the microminiaturized orthosis, however, could not be completed during the granting period because of delays in obtaining miniature electronic components.

The construction design of the electrical orthosis triggered by joint motion was changed to optimize hand function. The lightweight brace was removed from the ulnar side of the forearm and hand and replaced by a cradle over the flexor surface of the forearm and a hinged band over the dorsal aspect of the hand (Fig. 7). A micro-switch was mounted on the brace at the wrist, allowing an electrical stimulus with an adjustable threshold of 5-25 degrees of wrist extension. The hand piece was designed to lock at neutral or in 10 degrees of extension, while at the same time allowing free range of flexion. This construction design was chosen to enhance finger extension, particularly for patients with spasticity. A StimPulse transcutaneous electrical nerve stimulator, donated by StimTech, Inc., was modified to be triggered by the micro-switch. The lightweight, miniature stimulator was mounted on the orthosis, forming a single unit on the forearm consisting of stimulator, electrodes and trigger. This design was chosen to make independent use of the orthosis by the patient outside of the clinic treatment area more feasible.

Clinical Program:

Hemiparetic patients who have moderate gross grasp and some arm placement control, but who lacks functional hand-opening ability are candidates for orthotic stimulation training. Following determination of optimal electrode placement and amplitude of stimulation, the clinical protocol required a patient to practice grasping and releasing objects of various size using only the orthosis-assisted hand. Each practice session was to last approximately one half hour.

Positional Placement Training

Equipment:

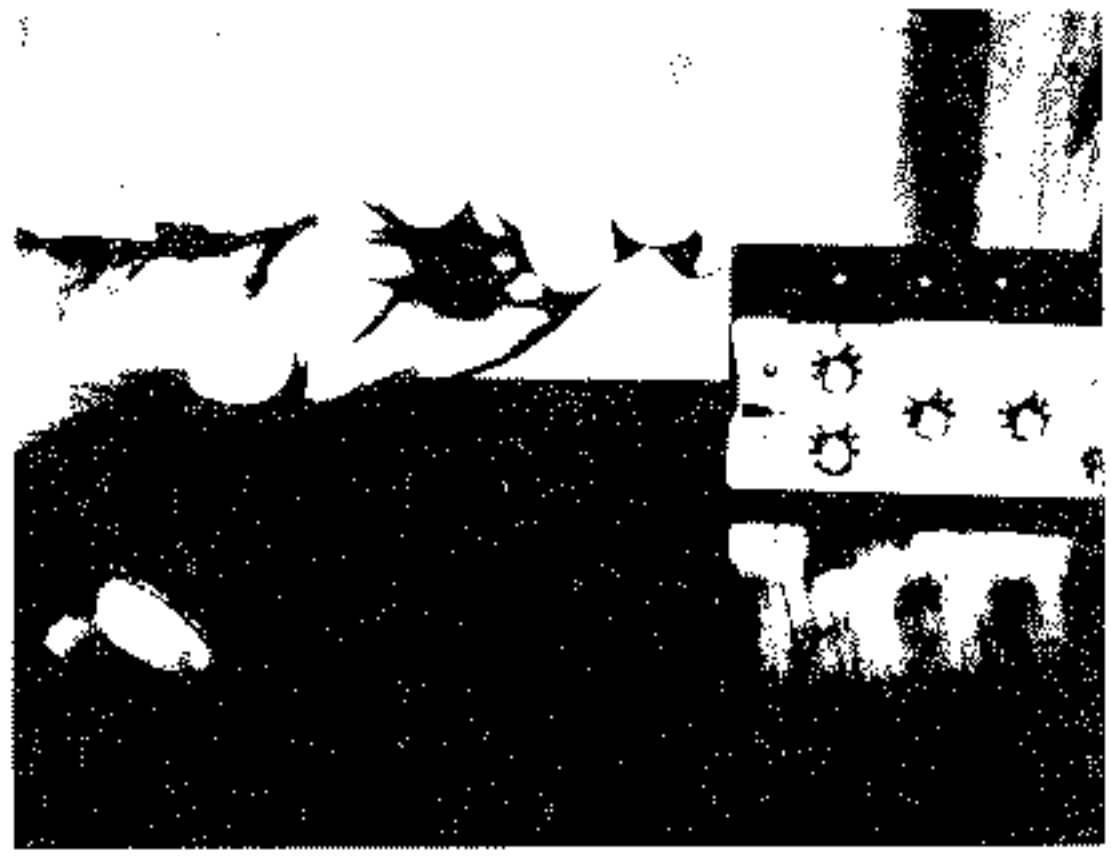

FIGURE 6. EMG activated electrical hand orthosis. Electrical stimulation for hand opening is triggered by EMG activity of wrist or finger extensors. EMG pick-up and stimulation may be accomplished using same or separate electrodes.

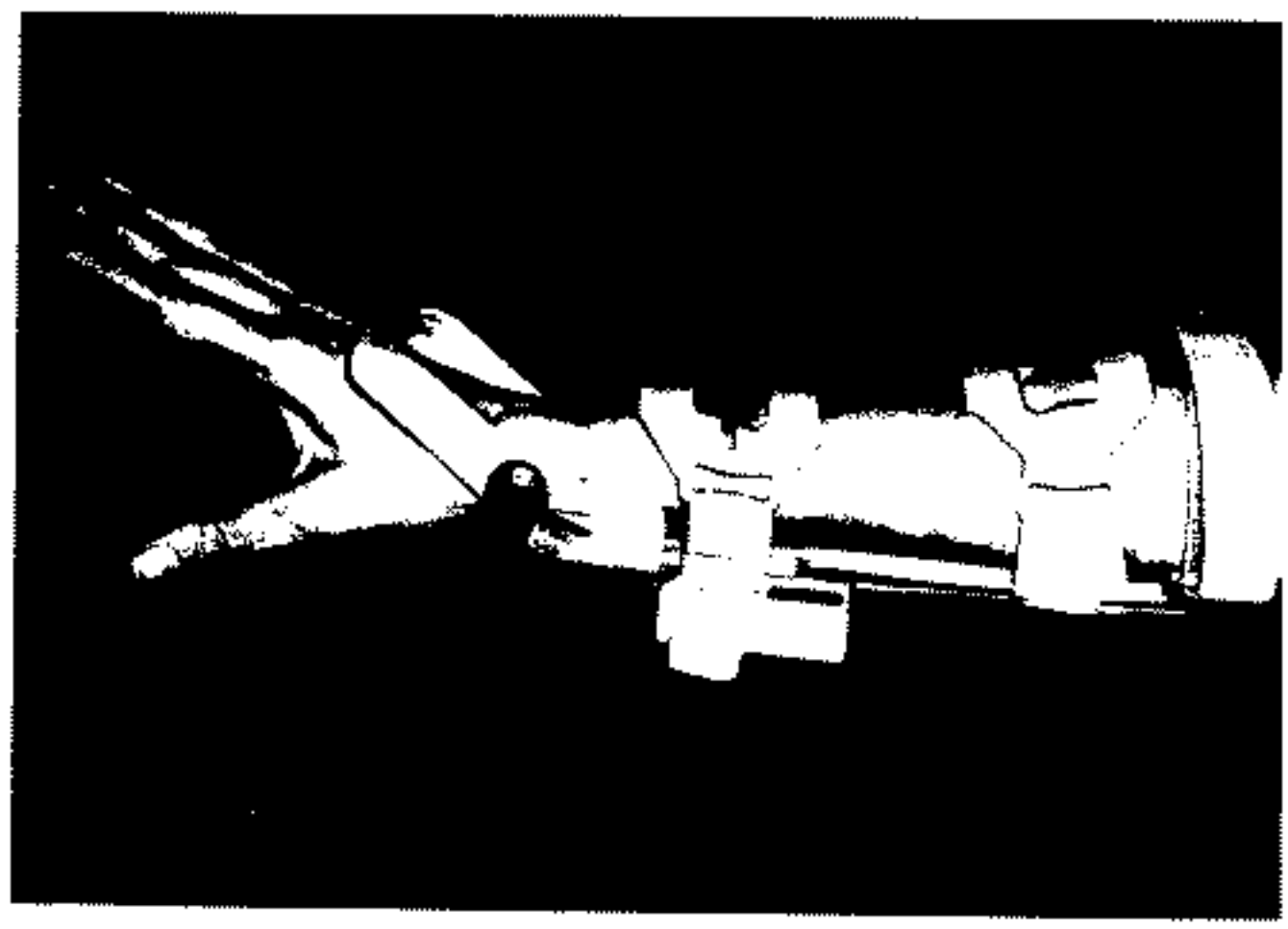

FIGURE 7. Motion activated electrical hand orthosis. A small amount of wrist motion closes micro-switch mounted on light weight brace to trigger electrical stimulation for hand opening. Stimulation is provided by miniature stimulator mounted on orthosis. Electrodes are held in place by velcro straps. The integration of stimulator, trigger and electrodes into compact unit worn on forearm makes use of orthosis outside clinic area feasible.

A microprocessor-based device was developed to help train controlled movement of the entire upper extremity through multiple degrees of freedom. This positional placement trainer consists of: 1) a table composed of a 7x7 matrix of glass switch plates, each of which is four inches square in size, sensitive to touch and capable of being individually illuminated (Fig. 8); and 2) a control box housing the microprocessor system and its associated switches and power supplies (Fig. 9). In operation the control box triggers the illumination of one of the 49 squares. The user must reach out and touch the appropriate square to darken it. This in turn triggers the illumination of another square. The selection of squares is random; the range of squares used, time and number of attempts allowed to contact the correct square, and total operating time are variable treatment parameters which may be chosen by the therapist. It is possible to position the table in either a vertical or horizontal orientation. The training device can calculate average response time, average number of attempts per destination square, and the total number of correct and incorrect contacts.

Clinical Program:

Clinical evaluation of the device is commencing at the current time, however, and data concerning its effectiveness should soon be available.

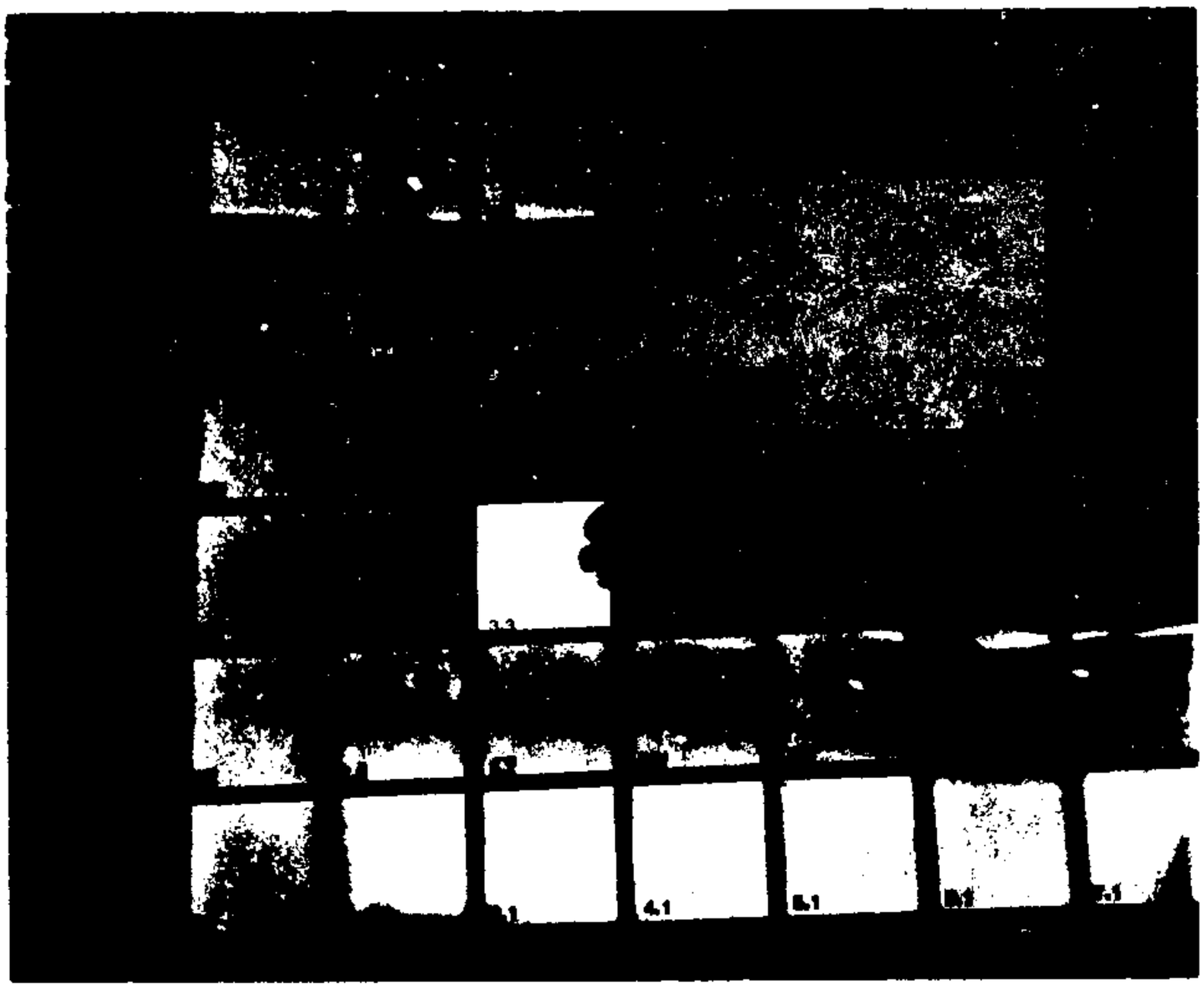

FIGURE 8. Upper extremity placement trainer. Hand contact is required to darken randomly illuminated, touch-sensitive glass plates. Successful contact of lit square triggers illumination of another plate. Plates are mounted on table which may be positioned either vertically or horizontally. In this manner a patient may train controlled movement of whole upper extremity through space.

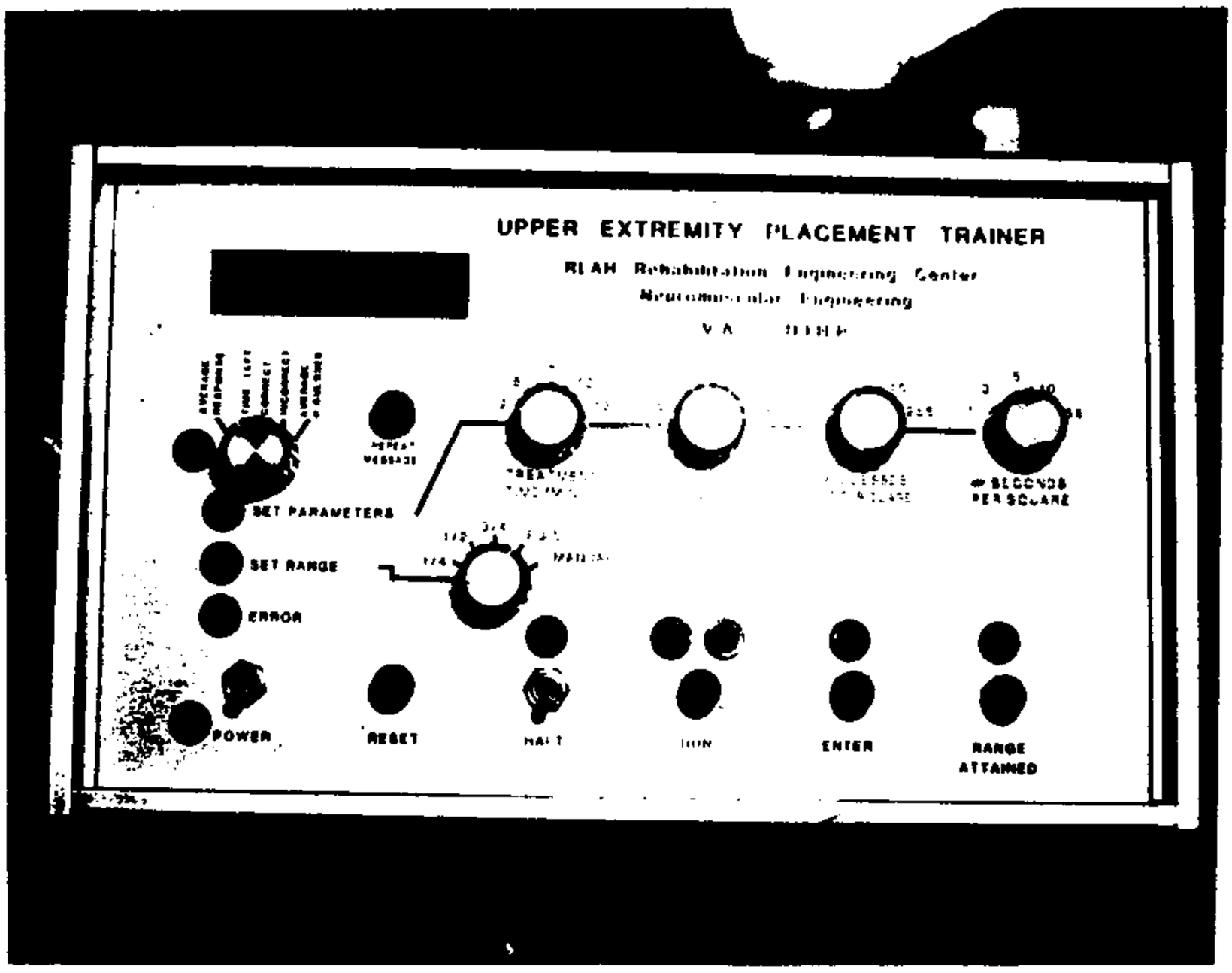

FIGURE 9. Placement trainer control box. Upper extremity placement trainer is controlled by a microprocessor, which allows variable programming of operating parameters and recording of quantified measures of performance.