Investigation of the Therapeutic Potential of FES in Improving Hand Function in Children with Cerebral Palsy

A Thesis

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by

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To Dad, Kris, and Gretchen
In Memory of Mom

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CHAPTER I
RESEARCH DESCRIPTION

1.1 Introduction

This research examines the possible therapeutic effects of a functional electrical stimulation, FES, program in the upper extremities of children with cerebral palsy. In particular, three boys with cerebral palsy participated in stimulation programs designed to improve function in their involved upper limbs. Emphasis was placed on increasing voluntary control of the wrist and thumb. Attempts were made to quantify changes in functionality that occurred during the programs by measuring the range of motion of the wrist and thumb, grip and lateral and palmer pinch strengths and the time needed to complete certain tasks developed for this study.

In conjunction, tests were run to address the feasibility of electronically controlling the on/off sequencing for the output of commercially available stimulators. Successful results led to the design and construction of an external, portable device prototype to drive up to four channels of stimulation according to user-defined timing patterns. This controller should facilitate the production of sequential movement with commercial stimulators.

A myriad of treatments ranging from surgery to music have been tried in attempts to alleviate cerebral palsy symptoms, which commonly include spasticity and difficulty in producing voluntary movement. Prior research in the field of FES outside of cerebral palsy has documented reductions in spasticity [1] and improvement in voluntary motion [2,3] after implementation of an electrical stimulation program. These results, therefore, suggest that FES might prove beneficial in treating cerebral palsy patients as well.

To date relatively few clinical trials of stimulation of palsied individuals have been conducted. Patient non-compliance with prescribed stimulation programs due to the fear or reality of the pain of the procedure and physicians' supposition of the same have significantly contributed to prevention of wider testing [4]. In some of the studies it has been concluded that all benefits were found to disappear as soon as the electricity was turned off [5,6].

In two case studies carried out at the Ohio State University very good compliance and encouraging results were obtained [4,7]. One of these cases, the thesis work done by Mozelewski, et. al., examined the use of electrical stimulation on the wrist extensor muscles of a twelve year-old boy[7]. By the end of the 18-week period an increase of over 70° had been made in the range of motion of the wrist and the strength of the wrist extensor muscles themselves had more than doubled. The greater range of motion allowed the boy to place his hand in a more mechanically advantageous position which led to gains in grip and pinch strengths.

Still, others have stated that although FES could produce improvement in the strength and range of motion of the muscles being stimulated, these benefits would not be manifested when the muscles had to be incorporated into a movement [6]. Thus, they theorized that FES would not produce functional changes in cerebral palsy patients. This thinking lies in contrast with the work done at

OSU which demonstrated marked improvement in the voluntary control of two cerebral palsy subjects [4,7].

1.2 Thesis Objectives

One of the main objectives of this research was to further examine whether an FES program could produce measurable voluntary functional improvement in the upper extremities of children with cerebral palsy. Specifically, the goal was to develope some quantifiable evaluations of hand function and use them to gauge the children's progress over time.

A secondary objective was to determine if an upper limit on amelioration in the affected limb existed. In other words, the question was whether the subject would continue to get better as long as he stayed in the stimulation program or would reach a point at which no further gain was possible. Another point of interest was the possibility of maintaining the advances produced by the FES program after discontinuing the stimulation therapy.

The other primary objective of this research was to design and produce a portable controller of commercially available stimulators in order to generate sequenced motions in the upper limbs. Prior work in coordinating movements in the lower extremities led to the development of controllers driven by manual switches [8]. The goal of this thesis work was to use electronic switches driven by a microprocessor. This would allow the user to program the controller for the desired stimulation timing of up to four different channels.

1.3 Design of Research

The original protocol of this research called for a single case study with the same boy who participated in Mozelewski's research. The FES program was to last for approximately 32 weeks.

By the end of Mozelewski's study the subject was already able to voluntary extend his wrist by 60° [7], but the use of his hand was still greatly hampered by a cortical thumb. For this thesis electrical stimulation of the thumb extensors and abductor was begun and excitation of the wrist extensor was continued in an effort to improve the performance of the hand and digits. This study fell within the guidelines previously approved by the Human Subjects Committee [7]. Commercially available, FDA-approved stimulators were used. After receiving initial instruction, the boy's parents supervised the stimulation at home.

As in the preceding OSU studies the subject was told to actively aid the stimulation in contracting the muscles of interest against imposed resistances. The original choices for FES parameters such as frequency, rise/fall times, electrode size, and electrode placement for the wrist extensors were continued from the Mozelewski study. These were later altered due to the results of tests run as part of this work. Proper electrode size and placement for the thumb were determined experimentally.

For the lower extremities functionality is usually measured in terms of gait. Data can be collected on parameters like peak velocity and distance to fatigue [4]. Since most normal individuals walk in a similar manner, a normal pattern for gait could be and has been established. Thus, changes over time in an individual's walking can be quantified in gait laboratories by comparison to this normal pattern.

Currently, no analogue exists for the upper limbs. Dexterity tests, therefore, had to be developed for this study to try to quantify possible changes in performance. The tests were comprised of the timed completion of tasks requiring the grasp-and-release and pinching motions, two movements basic to normal hand usage.

Six dexterity tests were created. The tests were run with each hand in order to provide some notion of the possible effects of learning the specific tasks through repetition. Multiple, timed trials of each of the tasks were to be conducted every three weeks. However, scheduling conflicts forced fluctuations in the time between testing dates.

The range of motion of the thumb was periodically measured with a goniometer in accordance with the theory that its increase would have to precede any functional improvement. Recording of the grip and lateral and palmer pinch strengths were continued from Mozelewski's study to ascertain if possible gains in performance might include increased strength of the grasping and pinching motions.

Significant gains in voluntary wrist extension and extensor strength, the generated torque having been assessed with a Cybex II machine, were noted in Mozelewski's thesis, covering an 18-week period. Measurements of these two quantities were performed in this study, too, in order to determine if the progress would continue.

After 19 more weeks of wrist extensor stimulation, for a total of 37 weeks since the boy began FES, the wrist extensor stimulation was ended. The subject still exercised the wrist in the same manner as he had with the electrical stimulation, but the movements were solely voluntary. The evaluations were continued to check for changes in the range of motion, strength, and function. Originally, excitation of the wrist extensor was to be permanently discontinued unless definite degradation in performance occurred. No conclusive worsening was observed; however, three months after ending electrical therapy for wrist extension, the boy sprained his involved wrist and stimulation of the wrist was then reinstituted to aid in rehabilitation. FES of the wrist was continued beyond the end of this study.

The single case study was expanded to three case studies when two more cerebral palsy subjects became available four months after the first, ongoing subject had commenced the stimulation program for this research. Again, FES was employed in the hope of attaining measurable functional improvement in the upper limbs. Stimulation programs were designed to fit the individual needs of the boys as cerebral palsy involvement in the two differed considerably. Thus, one boy received FES for the wrist, thumb, and fingers while the other only had his wrist extensor stimulated. The regimen of FES therapy employed was updated throughout the programs in correspondence with visual observations of performance made during periodic examinations.

Measurements were taken once every two weeks for one subject and once every week for the other participant. The testing frequency varied due to the much greater proximity to the OSU campus of one of the boys' homes in comparison to the other. At least two testing dates were held before beginning any stimulation. The quantities assessed were wrist and thumb range of motion, grip strength, lateral and palmer pinch strength, and the time required to perform three of the dexterity tests used with the first subject.

In working toward the goal of improving everyday use of the upper limbs, tests were run to try to maximize the subjects' physical response for a given level of discomfort. As mentioned before, pain is a critical limiting factor in employing FES in children with cerebral palsy. Thus, to derive the greatest possible advantage from the stimulation the response at the subject's threshold for pain tolerance should be optimized in terms of producing the biggest possible contraction while still limiting the spillover excitation of other muscles to a functional level. The FES parameters of electrode separation distance, the size of the ground electrode, and the frequency, rise/fall times, and amplitude of the stimulation were examined to determine if they did significantly affect the pain and response levels.

The development of the controller for the commercial stimulators was conducted in parallel with the clinical FES research. The first step entailed examining the feasibility of using an electronic switch to drive the stimulators. Tests were run to determine how quickly the stimulators could respond to being turned on and off. Then, a prototype device to sequence the timing of up to four different channels was designed and the hardware was assembled on a breadboard. The accompanying software was written and the device was debugged using an HP 64000 Emulation System. Finally, a controller able to operate without any supporting electronics was built on a perfboard using wire wrapping techniques.

CHAPTER II

SURVEY OF PAST WORK WITH ELECTRICAL STIMULATION

2.1 History of Medical Uses of Electricity

For centuries people have attempted to use electricity to treat a variety of illnesses and disabilities. In the Roman Empire Greek and Roman physicians advised contact with an electric fish, the torpedo fish. Records from the first century A.D. show that Scribonius Largus prescribed electric shocks from the fish as a cure for headaches and gout, and Dioscorides did the same as a cure for hemorrhoids [9].

John Wesley in a 1759 writing extolled the virtues of electric shocks in relieving sciatica, kidney stones, and angina pectoris [9]. Benjamin Franklin administered shocks as treatment for convulsions and paralysis.

By the late 1800's numerous people hailed electricity as a panacea. Electric baths, electric belts, solenoid cages, and a wealth of other electrical devices advertised in catalogues, some under headings such as "Medicine Rendered Useless" promised to do everything from curing impotence to exorcising demons [9].

In the 1930's application of electricity actually did produce some remarkable medical results, most prominent among them being Albert Hyman's resuscitation of a number of patients [9]. Successful employment of an artificial pacemaker occurred twenty years later.

Today, electrical stimulation is being applied in a variety of medical applications including efforts to reduce pain, encourage bone growth, control epilepsy, and lessen muscle atrophy and spasticity. Medical and engineering personnel have also focused on the implementation of electrical stimulation to produce functional contraction of skeletal muscle; this treatment is part of a category of rehabilitation therapy called functional electrical stimulation, often referred to by the acronym FES.

2.2 Development of FES

The roots of FES date at least as far back in time as the conclusions drawn by Alessandra Volta in the 1790's[9]. He postulated that the muscle contractions he induced in frogs' legs by touching their leg muscles with a bimetallic rod were produced by the electricity from an external source, the rod, being applied to the nerve or muscle. About 70 years later the physiologist G.B. Duchenne identified all the locations in the skeletal neuromuscular system where the application of electricity produces the best contractions in his book Physiologie des mouvements [9].

FES using portable stimulators was first employed to correct dropfoot in hemiplegic stroke patients. Developmental work in the 1950's culminated in a paper written by Liberson, et. al. [10], describing the use of a heel switch which triggered stimulation of the peroneal nerve in the opposite leg. Pressure caused by the heel striking the floor resulted in contraction of the dorsiflexor muscles in the other leg, thereby preventing the foot from dragging during the swing phase of the gait.

Interest in FES grew greatly in the 1970's, due largely to the efforts of researchers in Yugoslavia. Gracanin, Vodovnik, Bajd, Kralj, and others working in the late 1960's and early 1970's developed their own electrical brace for dropfoot [11], extended stimulation to multiple channels with sequencing to generate improved gait [12], examined stimulation of the wrist and fingers of hemiparetic patients [13], and researched the effects of electricity on spasticity. Of great importance was their large clinical implementation of FES. They estimated that by 1981 3000 of their electrical, peroneal braces had been employed [14]. Their work helped spark activity by other scientists, such as Vossius, Weed, Merletti, Peckham, Mortimer, et. al., who have developed functional electrical stimulation systems for both the upper and lower extremities.

FES technology has become increasingly sophisticated. Fully implantable systems driven by external RF sources have been built and tested [15]. Quadriplegics have performed sequenced movements through the use of computer-driven stimulation based on the EMG's of people with normal neuromuscular function [16]. Scientists are looking at the possibility of using one's own EMG signal to provide feedback to drive the FES[17].

2.3 Therapeutic Implementations of FES

Many of these complex systems use functional electrical stimulation as a type of orthotic aid. The stimulation enables the persons to perform certain movements which they could not do on their own due to irreparable neural damage. Once the electricity is turned off, the benefits are lost. Another use for FES is as rehabilitative therapy; the stimulation restores some voluntary function by initiating physical changes in the body.

One goal, dating back to Duchenne, of some of these restorative treatments has been to reduce muscle spasticity. A paper by Lee, et. al., published in 1950 described the qualitative diminution of tone for an average of six hours after applying electric current to the spastic muscles of 27 paraplegics [18]. However, the degree of relaxation did not increase with succeeding treatments. A paper released two years later discussed the positive results attained in four patients by exciting the muscles antagonistic to the spastic ones [19]. The researchers noted a decrease in baseline tone in the patient, whom they observed for three months.

Another scientist also expounded upon the superiority of stimulating the muscles antagonistic to those displaying hypertonicity[1]. Relaxation occurred in 87 of 96 hemiplegic subjects and was still evident 4-16 weeks after treatment in 58 of 64 cases examined, as determined by use of the Ashworth scale.

Yugoslavian researchers noted additive effects when stimulating the antagonists, too. Five of six hemiplegic patients experienced marked reduction in tone over a six-month period of treatment as measured by a decrease in resistive torque[20].

Yet, another study actually measured an increase in spasticity over time when the hypertonic quadriceps muscles themselves were electrically excited[21]. Twenty-one subjects suffering from spinal cord injuries demonstrated an increase in tone after four weeks of treatment, as measured by the pendulum drop test. Results in eight patients after eight weeks of the program were mixed.

Investigators have made claims that other benefits invoked by the use of FES have continued after removal of the electricity. Mooney, et. al., recorded the improvement of gait resulting from three weeks of treatment; 15 minutes of stimulation once a week preserved the improvement [22]. Carnstam, et. al., also observed improvement in voluntary gait after use of FES [2]. Vodovnik and Rebersek developed a physiological model for their proposal that long-term effects of FES "...are due to neural changes in the subcortical and spinal structures[3]."

2.4 Past Studies of FES with Cerebral Palsy

Promise of relief of spasticity and of effects which carry over after the removal of the current seemingly point to a great potential for FES in treating cerebral palsy, a neuromotor deficiency manifesting itself in severe spasticity in a number of cases, as well as in difficulty with posture and voluntary movement. Yet, the number of studies conducted in this area is not large, and the conclusions drawn from the studies that have been performed are often quite conflicting.

The medical personnel in Ljubljana, Yugoslavia have applied FES to by far the greatest number of children with cerebral palsy of any research group. Already in 1974 Gracanin described the use of FES to improve gait in cerebral palsied children[23]. By 1981 peroneal and tibial nerve stimulation had been tried on approximately 250 children (the numbers in different reports are a little inconsistent) with improvement in gait observed in 200 cases [14]. Treatment consisted of wearing for 4-5 hours a day a brace system in which a heel switch initiated stimulation in the opposite leg. The criteria for gait improvement were not specified.

Nine of these subjects were studied over a twelve-year period [24]. Presence or absence of 30 variations from normal walking posture was noted in three trials of voluntary gait: the first examination transpired before the commencement of the stimulation program, the second after four years, and the third after twelve years. The total number of gait irregularities in the nine participants dropped from 173 to 159 to 146. However, the experimenters concluded that continued FES would still be necessary as amelioration had been insufficient to enable walking without the external excitation.

Other people investigating this area have related seeing almost no effects of FES carry over once the stimulator was turned off. Researchers at the Hugh MacMillan Medical Centre noted betterment in measures of walking such as ankle dorsiflexion, knee extension, and step length when the peroneal nerve was excited during the gait in case studies involving two diplegic and one hemiplegic cerebral palsy patients [6]. However, they did not observe any statistically significant changes in voluntary walking in the ten cerebral palsy subjects who had been undergoing peroneal nerve stimulation for 30 minutes daily for periods of time ranging from two months to one year [25]. They concluded that FES could produce increases in strength and range of motion of given muscles, but that these improvements are not manifested when the muscles must become incorporated into a movement, such as walking. Gait analyses were performed using foot pressure and EMG recordings and the videotaped motion of joint reflectors.

A paper from Case Western University also reported that little improvement was sustained once the stimulation was removed. In the experiment six cerebral palsy patients had employed an FES system, in the attempt to correct dropfoot, for 40 to 60 minutes a day for up to a year. Striking advances in duration of floor contact with different parts of the foot and in the heel landing before the toe were seen when the stimulator was in use, but "...the dorsiflexion produced while the FES was in use was lost immediately when the stimulator was turned off [5]."

Yet, in another Case Western report two of seven patients who used FES for five months to a year did demonstrate noticeable changes toward a more effective walking pattern in terms of the heel-toe pattern [26].

An article written by British researchers describes the progress in voluntary dorsiflexion, gait, and weight-bearing made by two three-year old girls with cerebral palsy who used FES [27]. Treatment consisted of exciting the anterior tibial muscle for one hour, three times daily, for 8 weeks.

The boy with diplegic cerebral palsy in the Murray study received 1 hour of stimulation three times weekly in the tibialis anterior and quadriceps and had two gait training sessions each week [4]. Walking velocity increased from 14 feet/minute to 200 feet/minute. The manner of his walking, as evaluated in the gait laboratory at OSU, also improved.

Previous work regarding the effects of neuromuscular stimulation on the upper extremities of cerebral palsy patients is scarce. Stimulation was performed on the extensor carpi ulnaris muscle for half of an hour per day for five days each week for five months on the subject of Mozelewski's research [7]. The subject's peak voluntary wrist extension increased by over 70° during the course of the stimulation program. Better wrist extension translated into a rise in grip strength of over 600%.

CHAPTER III
CEREBRAL PALSY

3.1 Description

Cerebral palsy, a disability first well documented and described by Dr. William Little in 1862 [28], is the most prevalent condition in handicapped children in the United States[29]. Studies from the 1940's and 1950's in America found 1.5 to 5 cases of cerebral palsy/1000 live births [30]. A 1978 study of 54,000 births found an incidence ratio of 5.2/1000[29]. Thus, the occurrence of cerebral palsy, referred to by the acronym CP, does not seem to be waning. In the early 1980's approximately 400,000 children living in the U.S. had been diagnosed as having CP[29].

Cerebral palsy is a non-progressive motor disorder caused by brain lesions which occur prenatally, at birth, or within the first few years of life[31]. By definition the damage to the immature nervous system does not change, although the effects of the lesions may certainly change as the child matures.

A variety of factors can produce these lesions. The most common causes are hypoxia, as may result from a kink in the umbilical cord , for example, reduced cerebral blood flow, intracranial bleeding, and kernicterus, the poisoning of nervous tissue by bilirubin passing through the blood-brain barrier; this can result from an Rh mismatch between mother and fetus.

3.2 Types of CP

Injury can befall almost any area in the brain, thereby generating a wide variety of disabilities. Physicians have developed different categories for CP based mainly on the varying physical manifestations of the injuries. The classifications have not been standardized but the generally accepted classes seem to be: spastic, dyskinetic, ataxic, rigid, and mixed. Figure 1 displays some of the postures commonly seen in people with cerebral palsy.

The most common type of CP, spastic, accounts for 60-70% of all cerebral palsy cases[28,30]. The signature symptoms include hypertonicity, hyperactive stretch reflexes, and a positive Babinski sign (when the sole of the foot is tickled, the big toe turns up rather than down.) The increased tone leads to the “clasp-knife” phenomenon [32]; the body folds up due to flexion at the elbow, wrist, and knee, and extension at the ankle. Other characteristics include clonus, a series of alternating contractions and relaxations, and contracture, permanent muscle or tendon shortening[32]. Spastics are affected more in the distal than proximal extremities, thus leading to greater problems with fine than gross motor skills.

Spastic CP has been further divided into subgroups describing the number and location of the limbs involved. Hemiparesis connotates motor difficulty of the arm and leg on the same side of the body, usually with greater disability in the arm. Quadriparesis describes the involvement of all four extremities, but the condition is more severe in the lower limbs. Some authors use the term tetraparesis when the affliction is equal in all four limbs. Spasticity limited primarily to the lower limbs is referred to as diplegia.

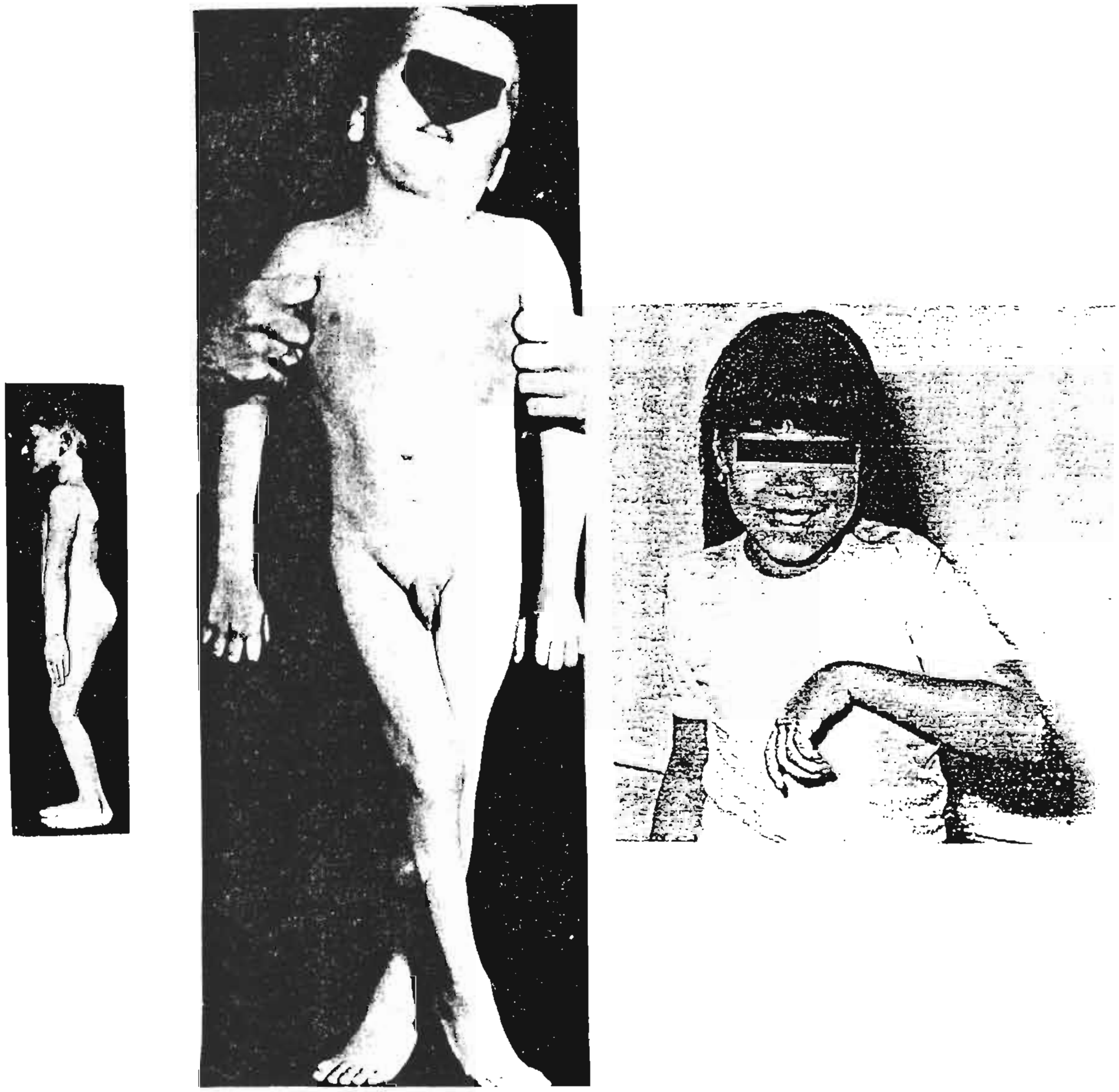


Figure 1 Typical CP postures [30,32]

Another class of cerebral palsy, dyskinesia, comprises 15-20% of CP diagnoses [30]. Dyskinesia encompasses a number of conditions, all describing a type of involuntary movement. With one type of dyskinesia, athetosis, attempt of a voluntary activity can initiate a sequence of smooth, slow, and writhing motions, primarily in the face and distal limbs [32]. Chorea is associated with asynchronous, spasmodic contractions in the face and extremities, while ballismus correlates with very coarse, jerking movements of the limbs. Dystonia is characterized by rhythmic, twisting distortions of primarily the trunk and proximal extremities.

Ataxia is a very rare form of CP which is quite disabling. It involves an inability to coordinate sequences of muscular movement

Rigidity is very similar to spasticity. "Lead-pipe vs. clasp-knife" hypertonicity clinically differentiates the two [32].

Of course, as multiple lesions may occur in many areas of the brain, a substantial percentage, 10-15%, of the cases involve a mixture of the previously mentioned types. Also, a number of other disabilities produced by brain damage are often present in conjunction with cerebral palsy. Of the people with CP 40-60% also suffer from mental retardation [30]. Epilepsy and seizure disorders appear in a similar number of palsied individuals. Other problems can include visual, auditory, and dental defects as well as impairment of communication. Abnormal muscle tone can cause hip dislocation and scoliosis. Behavioral abnormalities such as a short attention span and hyperkinesis may also result.

3.3 Physiological Basis

Theoretically at least, the classifications should have their basis in the location of the neural damage. The large amount of integrative processing performed by the brain has made pinpointing and substantiating the correlation difficult, but people in the field have become increasingly confident of their hypotheses[28].

Contraction of all skeletal muscle is ultimately performed by activation of the alpha motor neurons which innervate the extrafusal fibers of the muscle. Control of contraction results from a complex integration of signals from a number of sources.

Muscles contain structures called spindles, (figure 2), which provide information about the length of the muscle. IA afferent nerves connected to the bag and chain fibers of the spindle synapse directly with the alpha motor neurons. Stretching the muscle fibers excites the IA afferent nerves which in turn excite the alpha motor neurons, thereby resulting in muscle contraction to counteract the stretch. The knee jerk response exhibited after striking the patellar tendon exemplifies this reflex. Figure 3 represents this neural loop.

The bag and chain fibers comprising the spindle are attached to the tendons by intrafusal muscle fibers innervated by the gamma motor neurons. The degree of contraction of the intrafusal fibers controls the stretch of the bag and chain fibers; their length determines IA afferent activity. Thus, primarily the gamma motor neurons determine muscle tone [34]. Suprasegmental control of tone is obtained via pathways from higher centers synapsing on the alpha and gamma motor neurons. Brain damage can hinder this higher influence, thereby compromising control of muscle tone.

Another sensory apparatus found in the muscle structure is the golgi tendon organ, located in the tendon connected to the extrafusal fiber. Contraction of the extrafusal muscle fiber elongates the golgi tendon organ, which then excites a Ib nerve; this afferent nerve then excites a spinal interneuron, which inhibits the alpha motor neuron.

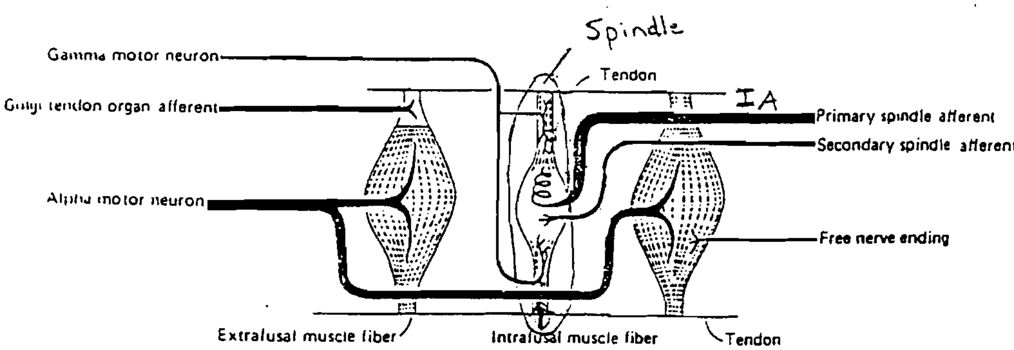


Figure 2 Muscle spindle [33]

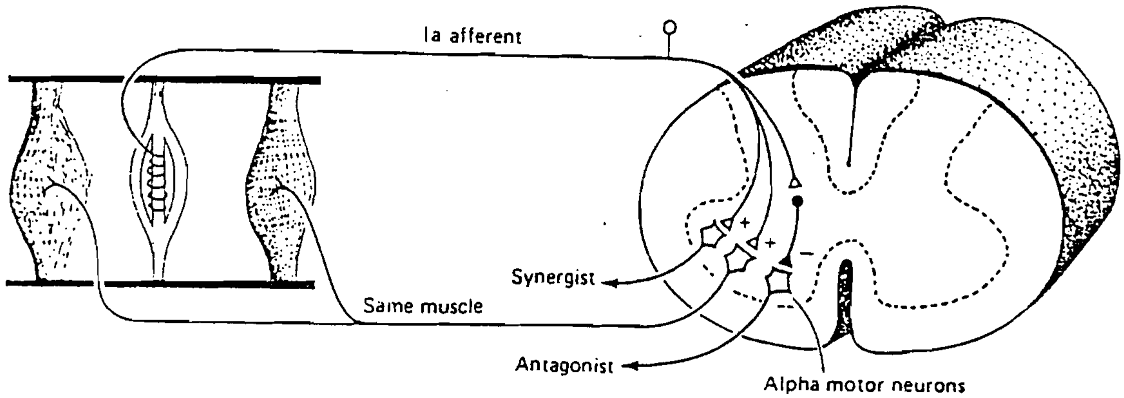


Figure 3 IA afferent - alpha motor neural loop [33]

Higher neural centers generally exert control by activating the spinal interneurons since IA nerve activity occurs so frequently. However, as previously noted, some brain centers do synapse directly on the alpha and gamma motor neurons. Cerebral palsy results from interruption of the neural pathways from the brain that control the interneurons and motor neurons. A model of the integration of the excitatory and inhibitory inputs is given in figure 4.

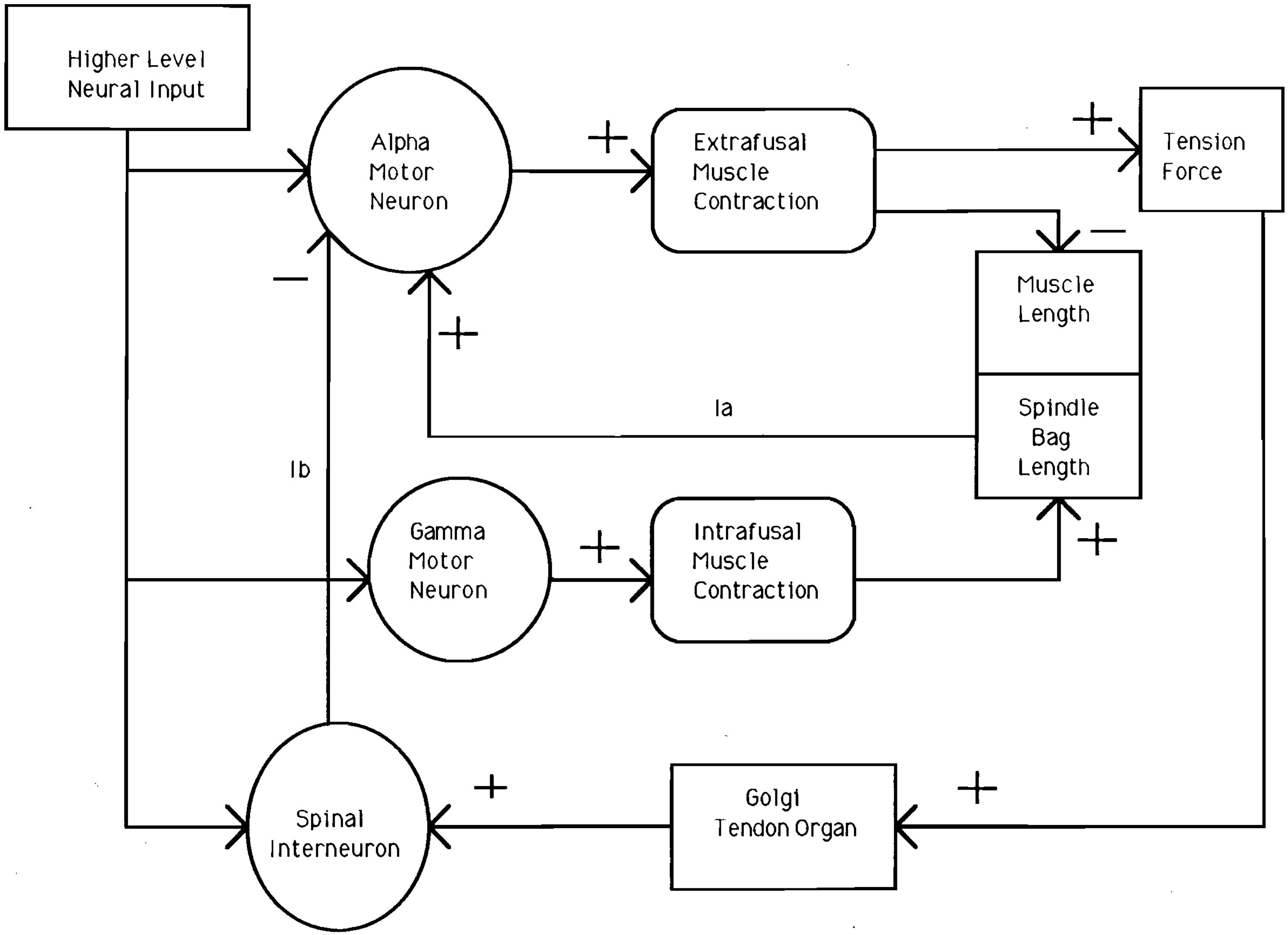


Figure 4 Model of neural integration of excitations and inhibitions [33]

Spastic cerebral palsy seems to be caused primarily by lesions in the pyramidal tract [34]. Comprised of the corticospinal and rubrospinal neural pathways, the pyramidal tract is usually associated with production of limb movement. The tract provides a direct connection between the motor cortex and the desired spinal interneurons. The corticospinal tract even synapses directly on the motor neurons innervating the musculature of the distal upper limbs. Thus, spastic individuals have difficulty with fine motor skills which require the use of muscles in the hands, fingers, and feet. Initially, infants exhibit flaccidity in the involved regions, but this evolves into spasticity. Some researchers claim that this is evidence of concomitant extrapyramidal tract damage[34].

The sensory and motor neural pathways lie close together, intimating that sensory involvement is quite possible. In fact, astereognosis and diminishment of two-point discrimination and proprioceptive sense often accompany spastic CP[32].

Dyskinesia results from damage to the extrapyramidal tract. This neural center, largely inhibitory in nature, primarily maintains posture and tone through the vestibulospinal and recticulospinal pathways. The basal ganglia especially is important in reducing muscle tone and preventing involuntary movement in order to allow voluntary motion. A majority of the dyskinetic disorders are thought to spring from lesions in the basal ganglia: athetosis from damage in the globus pallidus and chorea from degradation in the caudate nucleus[34]. Ballismus supposedly results from damage to the subthalamus.

The extrapyramidal tract has connections to centers of communication in the brain. Thus, dyskinesia often entails communicative problems [34].

Ataxic cerebral palsy seems to correlate with injury to the cerebellum or the vestibular or proprioceptive sensory systems. The cerebellum is responsible for coordination of motor programs with sensory input. The vestibular and proprioceptive systems in particular provide feedback vital for smooth motion. Degradation in any of these areas compromises the ability to make the needed comparison between desired and actual performance. This leads to difficulty in performing coordinated motion sequences, poor spatial ability, and poor sense of speed [34].

Coupled with the lack of voluntary motion resulting from lesions in the various pathways is the inability to override primitive reflex patterns. Neonates exhibit specific movement patterns in response to certain stimuli. These reflex patterns help control motion, tone, and posture while the nervous system matures. In normal children the developing higher brain centers eventually dominate the reflex patterns and the reflexes change. However, the neural damage in cerebral palsy children often prevents this evolution; the vestigial primitive responses can greatly hinder voluntary movement. In fact, much of the disability in palsied individuals results from these lingering reflexes[32].

For example, the grasp reflex denotes the immediate flexion of the fingers or toes when the palm or sole is touched [32]. This activity can carry over in spastics so that they have a very difficult time opening their hands in preparation of grabbing an object or uncurling their toes when trying to walk. Other primitive responses often associated with spastic CP are the tonic labyrinthine reflex in which the arms are flexed , wrists curled, and ankles extended in response to moving the head forward and the positive supporting reflex involved in maintaining an erect posture [30].

Neonatal patterns are exhibited in other types of CP as well. Two such reactions are the Moro reflex, the immediate abduction and adduction of the arms elicited by an unexpected stimulus, and the tonic neck reflex in which rotation of the head yields extension in one-half of the body and flexion in the other half[32].

3.4 Treatment

Much of the past treatment of cerebral palsy has focused on prevention of the primitive reflexes. The frequently used Bobath method of muscle training involves placing and keeping the child in a position which physically precludes the immature response patterns. Very intensive in terms of required physical therapist and parental time, the Bobath muscular retraining, like most CP treatments, has not shown conclusively positive results. Orthoses have also been used to prevent the movements. One study of the use of an orthotic aid to prevent a cortical thumb reported good short-term results [35]. Long-term benefits were not ascertained in this paper.

Orthoses are commonly employed by spastic children to improve posture and prevent damage to joints and soft tissue. Casting has also been used in efforts to lessen muscle imbalance and impede hyperreflexia.

Surgical treatments can also prove advantageous. Lengthening the Achilles tendon can alleviate problems originating from contracture. Adductor tenotomy may reduce leg scissoring. Upper extremity operations serve largely to stabilize the joints rather than to increase dexterity [7]. Approximately 5% of palsied individuals may benefit from operations in the upper limbs, about half the number for which surgery in the lower limbs could prove useful [7].

Certain drugs may be effective in combating hypertonus. Diazepan often works, but is likely to cause drowsiness. Mixed conclusions have been drawn about the benefits of dantrolene sodium. Its side effects include fatigue, nausea, and a small risk of hepatitis [29]. Injections of alcohol solutions have enjoyed success in a few trials.

A host of other treatments has been tried as well. Biofeedback has been suggested as a method to compensate for possible sensory loss. A fair amount of research has been put into electrically stimulating the cerebellum to alleviate seizures. People have tested the pain-relieving effects of acupuncture. Some have proposed using music as therapy.

The wide variety of treatments proffered clearly illustrates that no single rehabilitation procedure works in every case or even in one case. Other avenues still need to be explored, both alone and in conjunction with other methods. FES may prove beneficial in some instances. As stated earlier, its employment in treating CP has been very limited.

CHAPTER IV
FES

4.1 Physiology of Normal Muscle Contraction

In normal individuals movement arises from the sequential activation of motor units. A motor unit consists of a nerve and all the muscle fibers innervated by that nerve. Each muscle fiber is innervated by only one nerve. Excitation of skeletal muscles is achieved by altering the electrochemical gradient between intracellular and extracellular fluid. Active and passive forces work to maintain ion distributions around excitable tissue such that the gradient is typically around 70 mV with the interior of the cell at a lower potential than the exterior.

Impulses originating from the brain or various sensory receptors self-propagate along the neural pathways by producing action potentials, (AP's), temporary changes in the electrochemical gradient across the cell membrane. If the voltage inside a nerve cell is raised sufficiently to reduce the gradient to a threshold level, somewhere around 50 mV, an action potential results [36]. Sodium ion channels in the cell membrane open, thus allowing an influx of positive sodium ions which depolarize a localized area of the cell. For a period of time, typically around 1 ms, that region of the cell actually becomes more electrochemically positive than the extracellular fluid. This, in turn, causes neighboring sodium channels to open; accordingly, the AP spreads along the length of the cell membrane. A representation of an AP curve is shown in figure 5.

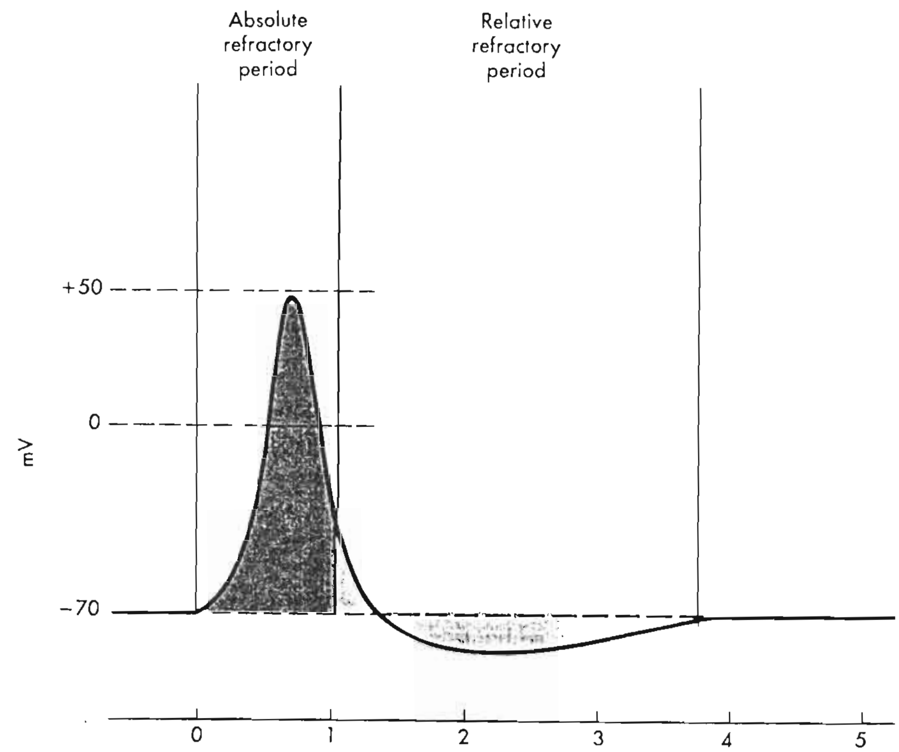


Figure 5 Action potential curve [36]

A fluid gap exists between the nerve cell axon and the skeletal muscle cell. The arrival of the travelling action potential at this neuromuscular junction triggers the release of acetylcholine from the nerve ending, The acetylcholine, having diffused across the junction, initiates excitation in the muscle fiber which culminates in an AP which races throughout the cell via the T tubule network traversing the fiber. The depolarization spurs the release of calcium ions from storage sites, the sarcoplasmic reticulum, inside the muscle. The calcium initiates contraction.

Although the AP in an alpha motor neuron results from the integration of a number of nerve signals, the action potential itself is digital in nature. The AP either occurs or does not occur; no gradations are possible. Coding for such parameters of muscle contraction as speed and force must be done by the frequency of the action potentials.

Physiological constraints limit the possible frequency range for AP's. Excitation results from a threshold amount of charge being delivered to the nerve in a prescribed amount of time. A slow build-up of charge can lead to accommodation, a state in which sodium ion channels are inactivated and other ion channels opposing depolarization are activated, thereby preventing AP production. If charge accumulation occurs too quickly to allow sodium ion activation, again, no AP is generated. This dependence on the rate, as well as the strength, of the charge delivery is illustrated by the chronaxie curve in figure 6.

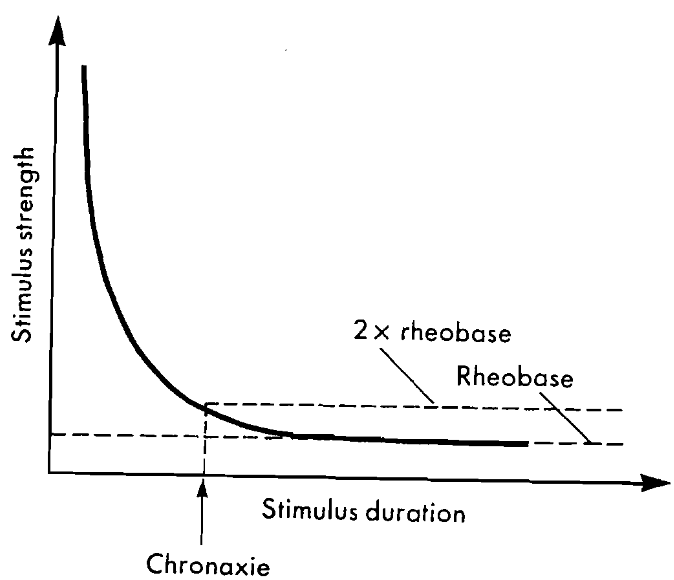


Figure 6 Chronaxie curve [36]

Cell mechanics also impose an upper limit on AP occurrence. After the initiation of an action potential, various ion channels must be opened and closed in order to restore the resting electrochemical gradient. During the absolute refractory period, lasting about 1 ms in motor neurons, the cell is still depolarized, so a new AP cannot be started. For a time of approximately 3 ms after that the formerly excited region of the cell will not experience an AP unless the stimulus is very strong since the gradient is typically 15mV greater than the resting potential during this relative refractory period. Thus, in the absence of very strong stimuli, an upper frequency ceiling of 250 Hz exists. In fact, some investigators have examined the use of suprathreshold AP production via electrical stimulation to block muscle contraction [37]. In anesthetized cats they placed both an electrode to elicit contraction and an electrode to block it. At a threshold around 200 Hz for the blocking stimulus they witnessed impedance of AP conduction. At 600 Hz the effect was almost a complete interruption of the nerve impulse.

At the muscle the AP frequency translates into force production. The muscle fiber has time to relax between excitations at low frequencies. The responses are termed twitches. At higher frequencies the contractions begin to fuse together, thereby resulting in additive force production. Above about 15-20 action potentials per second the contractions overlap completely. The muscle fiber produces maximal force in this state of tetanus. Figure 7 illustrates the difference.

Strength of contraction for the whole muscle is also mediated by the number of motor units excited. The smallest muscle fibers are stimulated first; other motor units are recruited as needed. During prolonged use motor units within the working muscle are asynchronously excited in order to prevent fatigue.

Unfortunately, FES has not yet reached the level of sophistication at which specific, individual motor units can be controlled. With FES the largest fibers, the quickest to fatigue, are the first ones to be excited. The same motor units are used throughout the contraction. Solomonow, et. al., have undertaken their research with the goal of producing graded contractions.

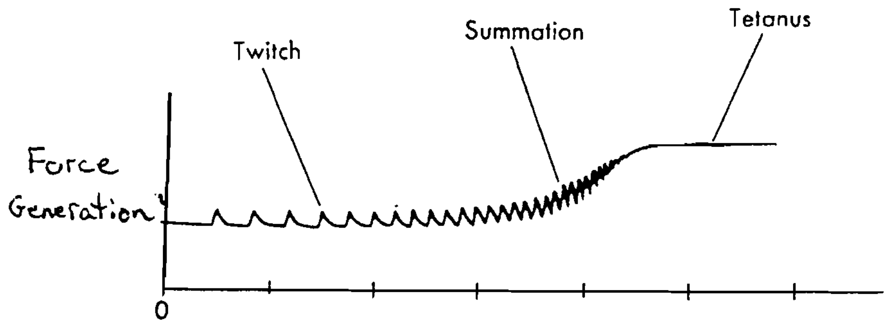


Figure 7 Muscle twitch vs. tetanus [36]

4.2 Mechanics of FES

Basically, the concept behind FES is to generate the necessary action potentials by external means since the person's body cannot produce them on its own due to neuronal deficit. This entails supplying enough charge in a given time, (in accordance with the chronaxie curve), to initiate the charge flow producing an AP. With FES one causes the threshold depolarization by making the extracellular fluid in the region of interest more negative than it is at the resting potential; in contrast the body generates AP's by making the intracellular fluid more positive. As dictated by personal preference one may view the FES process either as pumping negative charge into the extracellular fluid or as creating an electric field which draws positive charge away from the fluid outside the cell at the location where one wishes to produce an AP. A diagram of FES current flow is given in figure 8.

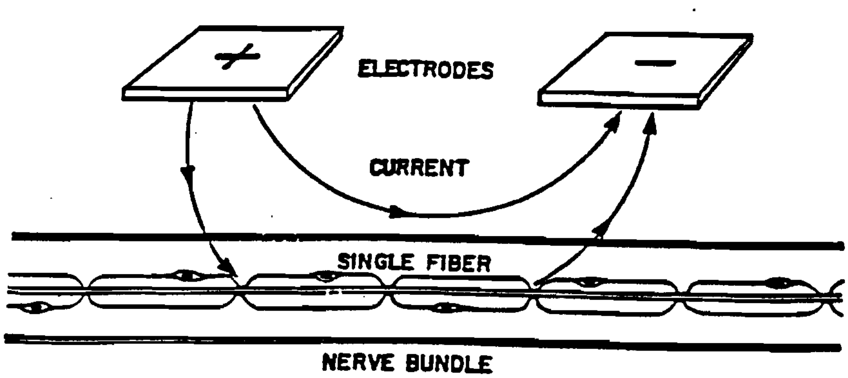


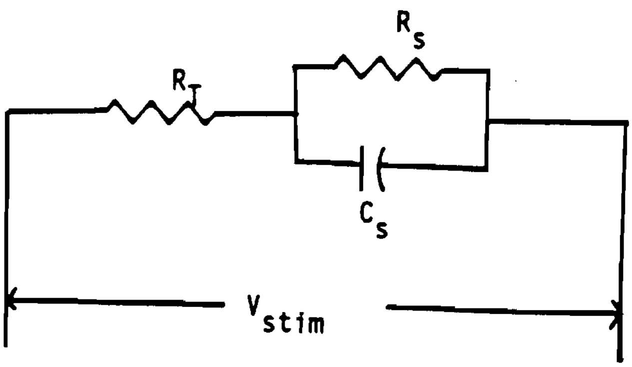
Figure 8 Model of current flow between electrodes [7]

4.3 Electrodes

In its simplest form FES requires only a source of charge, an electrode by which to transfer the charge to the body, and a cable to connect the two. However, FES technology has become increasingly advanced and now offers a number of options as to how and in what manner electrical charge is supplied. For example, electrodes may be placed on the skin surface, passed through the skin such that they directly contact the area of interest, or even sewn into the epimysium surrounding the muscle. The supply systems vary accordingly. Each type has its advantages and disadvantages over the others. For instance, the intramuscular electrodes afford superior muscle differentiation with smaller energy consumption.

However, they also can be dislodged or broken and carry the risk of infection.

With surface electrodes the charge must pass through several layers of tissue before reaching the desired nerve or muscle. Typically, the three layers of the skin, the stratum corneum, the epidermis, and the dermis, muscle tissue, and fat tissue separate the electrode from the region of interest. Each tissue contributes to the overall impedance. At frequencies used in FES the muscle, fat, epidermis, and dermis are largely resistive while the stratum corneum has a significant capacitative component [38]. The impedance is often modeled as in figure 9.



$R_S \gg R_T$

R_S = Resistance of the skin

R_T = Resistance of the tissue

C_S = Capacitance of the skin

Figure 9 Model of skin and tissue electrical impedance [4]

Figure 10 depicts a single pulse of electrical stimulation across a purely resistive load and a pulse as seen at an electrode located on a human forearm while figure 11 shows trains of each. The capacitative impedance of the skin is readily apparent in the saw-toothed shape of the pulses and the discharge between pulses.

If undamaged, nerve cells have a lower threshold depolarization level for AP production than muscle cells. Thus, the AP's causing muscle contraction are actually produced in the nerves exciting the muscles[38]. Action potentials can be initiated at almost any point along a peripheral nerve, but the excitation threshold depends on the location. The region with the lowest threshold, the motor point, is in close proximity to the neuromuscular junction [38].

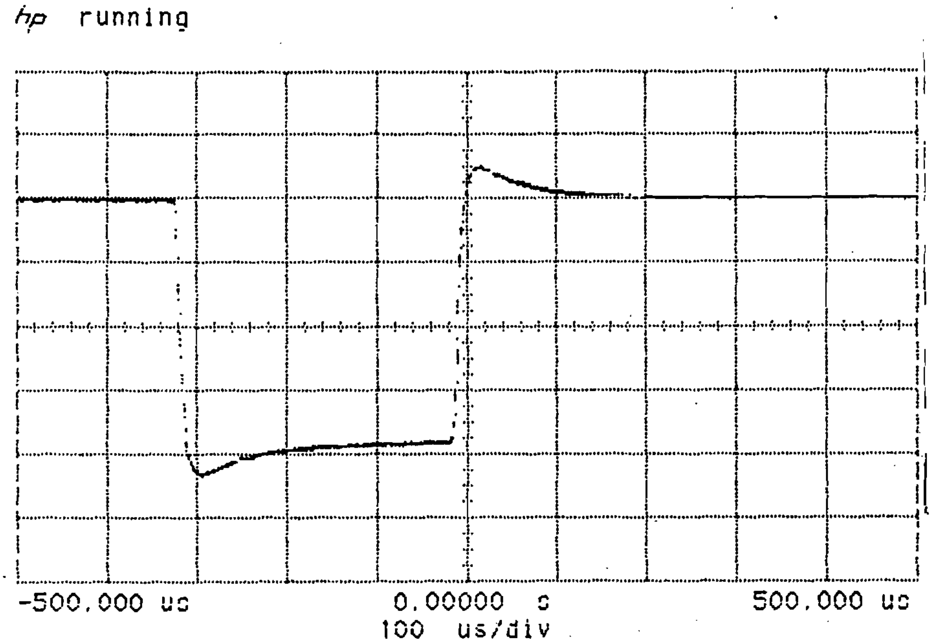
Ideally, one would like to ascertain the location of the desired motor point and calculate the charge flow needed to generate the correct electric field to excite that point. Unfortunately, the non-linear, frequency-dependent, anisotropic, and time-variant electrical properties of the tissues make modeling very difficult.

4.4 Pain

Just as motor neurons can be excited by external electrical stimulation, so too can sensory neurons be stimulated. Pain receptors and nerves which carry pain information are subject to activation during FES. The skin, especially, contains a large density of pain receptors[4].

The nerves carrying the pain information, type III and IV fibers, are smaller in diameter than the Ia motor neurons and, therefore, have higher impedance to current flow. This translates into AP's being initiated in motor neurons at lower thresholds. However, as

a)



b)

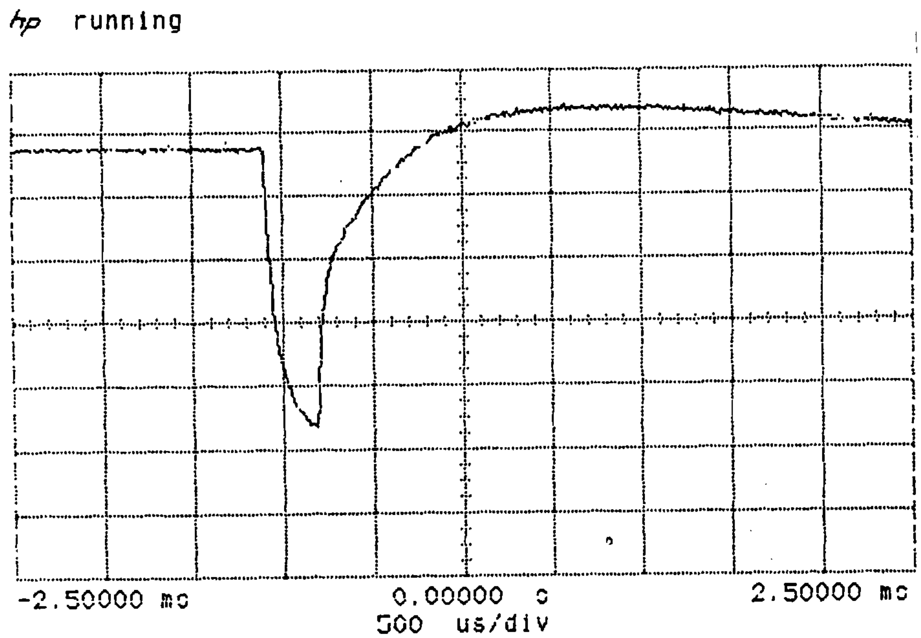
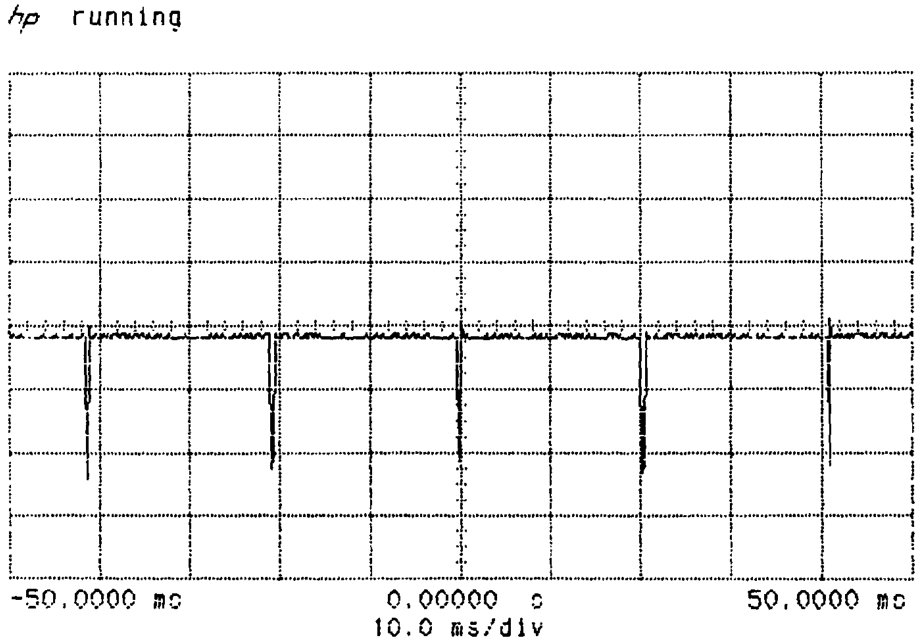


Figure 10 Single stimulation pulses as seen at the loads imposed by a) 56 kΩ resistor b) human forearm

a)



b)

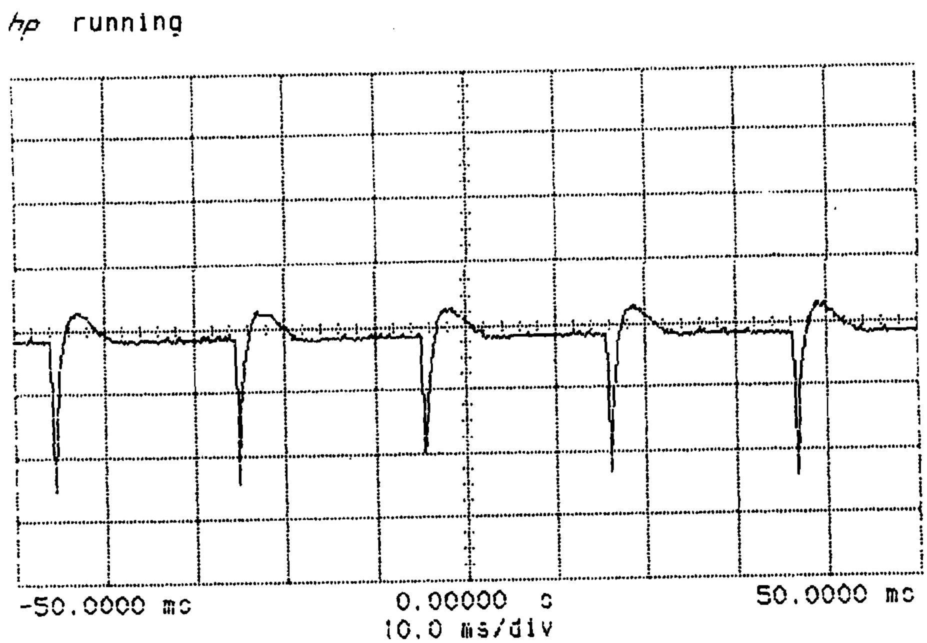


Figure 11 Train of pulses across a) 56 kΩ resistor and b) human forearm

more charge is supplied in an attempt to stimulate more of the motor units for a given muscle, more pain will be sensed. In individuals with normal pain sensation the pain tolerance threshold will determine the level of stimulation that can be used.

Pain feedback can serve as an important safeguard against excessive charge pumping in FES. Yet, low pain tolerances can hinder the effectiveness of an FES program or even prevent its use entirely. Many of the parameters associated with electrical stimulation are chosen on the basis of pain reduction.

4.5 Past Research in Optimizing Stimulator Parameters

The ways by which charge is supplied to the electrodes can also greatly influence the sensation of pain as well as affect muscle response. Signal type, shape, frequency, duty cycle, and transient characteristics have been examined in efforts to optimize the charge delivery.

Unfortunately, the relationship between these parameters and the body's response is highly non-linear. Optimization attempts based on varying one or two parameters while holding the others constant may yield only local rather than absolute maxima or minima.

Theoretically, one could scan the space of all possible parameter combinations to truly find the best response, but practically this is obviously impossible. A survey of literature reveals that most scientists compare one or two FES parameters while holding the others constant. Other difficulties can result when trying to analyze the conclusions of the studies that have been done. Pain is a rather ambiguous entity which is almost impossible to quantify. Tolerance of pain can very greatly from one individual to the next.

Muscles come in different shapes, sizes, and locations. What may work well in one muscle may not in another. One group discovered that 35 Hz was a good stimulation frequency for the large quadriceps, but that 50 HZ was much better for the smaller musculature of the upper limbs [39]. Procedural differences can lead to seemingly conflicting results among several papers. FES parameters will have to be customized for each person receiving stimulation. Still, past research can provide some very important guidelines.

4.5.1 Output Mode

One of the parameters which scientists have looked at is the type of charge source used. Specifically, some have tried to determine whether using a voltage source as opposed to a current source plays a role in altering the pain experienced. However, it seems as though the output mode is inextricably linked to the pulse shape. One study found a preference for voltage-regulated stimulation of the peroneal nerve when attempting to produce constant torque with rectangular and exponential pulses in 10 subjects [40]. The preference was statistically significant, but not overwhelming. Yet, another paper reporting on excitation of the quadriceps in 23 volunteers noted that while the participants slightly favored a voltage source when the stimulation consisted of asymmetrical pulses, they liked a current source better with symmetrical pulses [41].

4.5.2 Wave Shape

Efforts to optimize the wave shape have yielded similarly inconclusive results. Typically, charge is delivered in the form of

DC pulses, bursts of high frequency AC signals, or medium frequency AC signals. A number of different possible signals are pictured in figure 12. One group saw little difference in pain threshold or performance between stimulation generated with rectangular DC pulses and that comprised of AC bursts[43]. The DC pulses did produce a more constant torque, but this may have been due to the fact that they were driven by a current source while the AC signals were supplied by a voltage source. A paper comparing DC pulses, AC signals, and AC bursts on the upper extremities reported similar results for the optimal frequency range of each signal type [42]. Both groups endorsed using the DC pulses as these signals are more power and cost efficient.

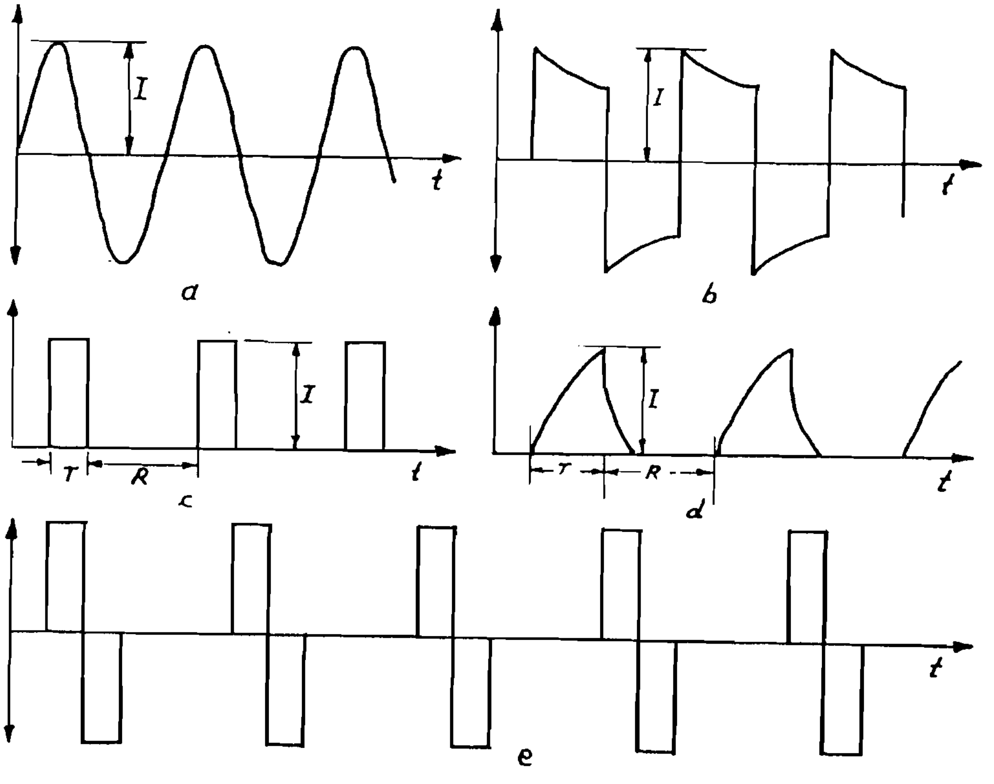


Figure 12 Possible wave shapes for FES signals: a)AC sine wave b)AC square wave c)DC rectangular pulses d)DC exponential pulses e)symmetric, biphasic rectangular pulses [42]

Numerous types of DC pulses have also been tried. Gracanin, et. al., tested four rectangular pulse shapes while keeping pulse length, frequency, and output mode constant [40]. Their subjects rated a regular DC pulse as preferential to biphasic stimuli or pulses with a DC bias. Exponential and rectangular pulses were indiscernible to the volunteers. Vodovnik, et. al., also detected almost no difference between these last two signals [42]. Bowman, et. al., however, wrote that their subjects favored biphasic to monophasic rectangular pulses [41].

4.5.3 DC Pulse Duration and Frequency

Greater consensus can be seen in the best choices for the pulse width and frequency when using DC pulses. Subjects in the Bowman study strongly preferred pulses of 300 μsec. to those lasting 50 μsec. when at a frequency of 35 Hz [41]. Trials of 300 μsec and 1 msec pulse widths in another report yielded superior comfort in most cases for the shorter duration[40]. A study which tested a range of pulse lengths at four different frequencies advocated using pulses lasting between 100 and 300 μsec. [42].

In the papers reviewed for this thesis general agreement existed that approximately 50 Hz was the optimal frequency for excitation of the upper limbs with DC pulses. As noted earlier tetanus does not occur below 15-20 Hz and above 200 Hz blockage of AP conduction begins. One paper examining stimulation frequencies up to 100 Hz found force generation to remain constant or decrease beyond 60 Hz [44]. Maximum force generation happened at frequencies between 50-60 Hz.

CHAPTER V
CLINICAL METHODS

5.1 Examination of FES Parameters

As described in the preceding chapter, a large number of choices exist in regard to the type of FES system and its corresponding parameters that may be employed. Decisions had to be made for this research regarding which choices would be good when using FES with cerebral palsy children. Originally, selections were based largely on what Mozelewski, et. al., working with the same equipment and the same boy, found to be successful [7]. During the course of this research cursory studies of electrode separation, size of the ground electrode, and the frequency, rise/fall times, and amplitude of the stimulation signal were performed and changes made according to the results. The major goal of these small studies was to determine if these variables did affect the response or level of pain. More detailed examinations should be part of future analysis.

5.1.1 Electrode Type

For this project the decision was made to use surface electrodes. FES was to be used as a therapeutic rather than an orthotic aid, so easy removal of electrodes was desirable. The three boys who participated in this study were still growing and were very active. One plays football on his high school team, another basketball on his 8th-grade team, and the third likes to bike and swim. Clearly, indwelling electrodes, which are subject to breakage and migration, were impractical.

Specifically, electrodes made of silicon rubber infused with carbon were used. The great flexibility of the silicon rubber enables fitting the electrodes to the contours of the body. Also, the rubber could easily be cut with a scissors to create electrodes of any desired shape or size. The inertness of the carbon electrodes was also very beneficial.

While the carbon-rubber affords good electrode-skin contact, these electrodes do have lower conductivity than the metal variety. As described by Cilliers, et. al., low electrode conductivity/body conductivity ratios can lead to “hot spots”, regions of high current density [45]. Thermal damage can result if the density becomes too high. In subjects with intact pain receptors and nerves, such as most CP patients, high current densities can also cause pain. The problem can be augmented by the drop in potential, produced by impedance in the electrode, across the electrode from the point where the wire carrying the current feeds into the electrode to its outer edge [45]. This creates even higher current density at the feedpoint. Yet, inspite of the possible problems with nonuniform current densities, the greater flexibility and inertness of the carbon-rubber commend its use.

5.1.2. Electrode Separation

Nathan, et. al., at Case Western empirically found “optimal” electrode location for stimulating muscles in the forearm and hand [46]. However, they were testing quadriplegics, so they were able to use very high current densities and a bipolar electrode arrangement.

Using a number of approximations, Cilliers makes the far-field estimation of electric field strength in the body at a distance R from the electrode to have been reduced in value by the factor $1/R^3$ when using a bipolar configuration [38]. He calculates that when two bipolar electrodes are separated by a distance greater than three times the radius of one electrode, the field generated may be treated as that resulting from two distinct monopolar electrodes. Cilliers models the field amplitude to drop only as $1/R^2$ when using a monopolar system. Thus, with the bipolar set-up much less unwanted spreading takes place, but the amplitude necessary to fully excite a muscle increases as well. This can produce pain in subjects with operational pain pathways.

As part of this thesis a simple test of different electrode separations was conducted on the extensor carpi ulnaris of a normal subject. Four distances were examined: 10.7, 7.0, 5.0, and 2.8 cm. The position of the active electrode was kept constant; the ground electrode was moved. At each distance the amplitude was raised until reaching the limit of the subject's tolerance. The amplitude changed only slightly, from 35 to 34 to 33 to 32 mA, though this was partly due to a bit of masochism. The stimulation did become increasingly more uncomfortable as the electrode separation decreased. The response, as measured by the degree of wrist rotation from the neutral position, fell dramatically from 65° to 50° to 52° to 40°. However, the amount of spillover excitation was lessened accordingly. The thumb extension and ulnar deviation witnessed at 10.7 cm almost disappeared completely at 2.8 cm. The response could be improved at the 2.8 cm distance by increasing the amplitude without noticeably affecting thumb extension or ulnar deviation, but the pain became excruciating well before the angle of wrist extension even approached that observed with the electrodes 10.7 cm apart. The electrodes used had a radius of approximately 1 cm so the smallest separation was about the limit for what could be considered a bipolar configuration. Trials with variously sized electrodes yielded similar results; the furthest possible separation correlated with the least pain and greatest wrist extension.

Seemingly, a choice must be made when using FES on children with cerebral palsy who can feel pain between the size of the response and the ability to attain muscle differentiation. The people involved with this thesis decided to optimize the response. All three cerebral palsy participants had hypertonic wrist flexors so that even the maximal response was at first quite small. Producing the largest movement possible was beneficial not only in strength training, but also in terms of visual feedback and psychology. Seeing the wrist move was important. Also, the targeting of muscles for induced contraction did not need to be very precise; coincident thumb extension with wrist extension or several fingers flexing rather than just one was quite acceptable.

5.1.3 Ground Electrode Size

Some researchers have stated that electrode size plays a relatively unimportant role in determining pain thresholds and discomfort levels[47,48]. Yet, Mozelewski ,et. al., noted differences in response when the size of the active electrode was changed [7].

In qualitative studies performed as part of this research one normal and two affected individuals did notice differences dependent on the size of the ground electrode used. The normal subject tried three ground electrodes with the respective surface areas of 220 mm^2, 325 mm^2, and 840 mm^2. In producing wrist extension best results were obtained when using the 325 mm^2-sized electrode as the ground electrode. With the largest of the three ground electrodes greater extraneous thumb extension and ulnar deviation were seen, although the discomfort felt by the subject was very similar to that experienced with the 325 mm^2-electrode. With the smallest ground electrode the unwanted movement was still seen while the pain increased and the wrist extension decreased by ten degrees. A further trial of thumb abduction was conducted in the normal subject. The best abduction was again attained when the electrode of 325 mm^2-area was used.

These results prompted a switch in the size of the ground electrode used by two of the boys with CP who participated in the FES study. FES conducted on the wrist extensor with the 325 mm^2-electrode felt much more comfortable to both boys than stimulation with the 840 mm^2-ground electrode. The amount of ulnar deviation and stray thumb extension decreased while wrist extension remained the same. Seemingly, ground electrode, as well as active electrode, size affects pain and response.

5.1.4 Stimulator

The Respond II® stimulator from Medtronics was used to invoke muscle contraction in this research. The Respond II® is a battery-operated current source generating monophasic rectangular pulses of 300 μsec width. These parameters are fixed, but prior studies have shown that these choices are actually quite good. The variables are the amplitude, frequency, rise/fall time, and on/off time of the stimulation. The Respond II® repeats a cyclical pattern; the muscles are made to contract for a given length of time and then are allowed to relax. The length of the excitation and rest periods are manipulated by changing the on and off times. The pulse width ramps up from 0 to 300 μsec at the beginning of the excitation period and gradually falls from 300 μsec to 0 at its end. One can alter the amount of time over which the pulse width crescendoes and decrescendoes by changing the rise/fall setting. Rise/fall times can last anywhere from .5/1 seconds to 8/3 seconds.

The amplitude of the current pulse generated by the stimulator remains constant during the entire excitation time. Yet, the amplitude of the voltage seen at the electrodes placed on a person will vary as the length of the pulse varies because of the capacitative nature of the skin. The voltage across a capacitor is given by:

$$V = Q/C$$

for a constant current source: $Q = I*t$

therefore, $V = I*t/C$

Thus, the longer the pulse lasts, the greater the voltage amplitude becomes.

One can also vary the number of rectangular pulses that are delivered each second by manipulation of the frequency setting. It has a range from 1-53 Hz. One may select a current amplitude for the rectangular waves from anywhere between 0 and approximately 100 ma.

5.1.5 Stimulator Variable Settings

Children with cerebral palsy usually have functioning pain, pressure, and thermal receptors. Minimizing pain is vital in attaining the continued participation of these children in an FES program. Toward this end a survey of the Respond II® parameter space was conducted on the forearms of six volunteers.

The test group consisted of four normal males in their twenties and two boys, aged 15 and 13, with CP. One of the boys had been receiving stimulation for 10 months on his wrist extensors at the date of these trials. His affected arm was used in this study. The other boy, who had not yet started any FES program, had both his involved and uninvolved arms tested. The extensor carpi ulnaris muscles were stimulated at four frequencies, (25,35,45, and 53 Hz), and three rise/fall times, (.5/1, 4/2, and 8/3 seconds), for a total of 12 different settings. The amplitude was increased at each setting until the limit of tolerance was reached. Participants were instructed to maintain the same level of discomfort for each of the 12 trials. The resulting angle of the wrist extension formed by the the raised wrist and the forearm was measured with a goniometer and recorded along with the corresponding stimulator amplitude setting. In this manner the effects of frequency, amplitude, and rise/ fall times were examined, albeit in a rather superficial manner. The results are located in tables 1-7. It should be reiterated that the rise/fall times describe the amount of time over which the train of stimulation pulses ramps up from an individual pulse width of 0 to the final value of 300 μsec. and the period during which the train decrescendoes back toward 0. These rise/fall ratios are in no way associated with the time required for an individual pulse to increase from 0 to its peak amplitude or to decrease from that maximum amplitude back to 0.

The sequential testing orders of the frequencies and rise/fall times were varied to guard against certain variable combinations being preferred merely because of accommodation and the subsiding of nervousness and unease occurring over time. Obviously, the small sample sizes preclude one from drawing any unequivocal conclusions from the data. Yet, the outcomes do suggest some points of interest for future consideration.

One fact stands out strikingly in all seven cases; the maximum amplitude tolerated at each setting remains remarkably constant for a given arm. For all 12 trials it usually stayed within the ±2 ma uncertainty associated with reading the current. The greater variations derived from the data of P.K. at 35 Hz and S.N. at 25 Hz are probably attributable to anxiety since these were, respectively, the first frequencies tested for both of these two and FES was still a rather new phenomenon for them. The only other aberration occurred at the 25 Hz stimulation of C.R.'s unaffected arm. Perhaps the toleration of a much higher amplitude was due to accommodation and fatigue since this was the last frequency tried.

In most instances it seems that the amplitude of the stimulation pulses determined the level of discomfort independently of the frequency and the rise/fall time. Changing the frequency or the rise/fall time while keeping the amplitude constant modified the response.

In the four men without CP and in C.R.'s unaffected arm, (see tables 1-4, 6), the amount of time for the pulse widths to increase to and decrease from 300 μsec. did not profoundly influence the size of the response. Angles at a given frequency in a given case are within ±2°, the uncertainty in measuring, for all three rise/fall times except for three instances at the setting of 25 Hz and 0.5/1 seconds; this was the worst combination in these three data sets. In some trials the the shortest ramping times produced rather violent jerking of the arm, but the extension attained and comfort felt were similar to those resulting from longer rise and fall periods.

In these 5 subjects frequency really determined the response. Depending on the person, the optimal number of pulses per second was 35, 45, or 53. Thus, no evidence was gathered in support of a single, best frequency.

The rates at which the pulse widths grew and shrank did play a more important role when FES was used on the two involved arms (tables 5 and 7.) The velocity of contraction affects the degree of spasticity in the antagonistic muscles. The faster the contraction is the greater is the resisting hypertonus. One can see in C.R.'s data that the shortest rise/fall time, 0.5/1 seconds, usually produced the worst response for a given frequency and never spurred the best extension. However, D.S. exhibited much less dependence on rise/fall time. Only at 53 Hz was the change in response resulting from a change in ramping time very significant. Furthermore, the combination of 53 Hz and 0.5/1 seconds coincided with the best overall response. He had been receiving stimulation in this arm for 10 months, so perhaps spasticity had been reduced sufficiently to lessen the velocity-dependent resistance.

To look at this possibility a little more C.R.'s affected wrist was tested again after 16 weeks of stimulation. The constancy of the amplitude can be observed once again in table 8. Of greater interest

Parameter Testing

Table 1 S. N. (Normal Subject)

	Rise/Fall Times (sec)		
Frequency (Hz)	.5/1	4/2	8/3
25	30° 45 mA	38° 48 mA	38° 48 mA
35	48° 49 mA	50° 49 mA	48° 50 mA
45	53° 51 mA	53° 51 mA	53° 50 mA
53	67° 51 mA	68° 51 mA	66° 52 mA

Table 2 P.K. (Normal Subject)

	Rise/Fall Times (sec)		
Frequency (Hz)	.5/1	4/2	8/3
25	50° 38 mA	52° 39 mA	48° 37 mA
35	51° 33 mA	52° 33 mA	50° 32 mA
45	61° 41 mA	62° 41 mA	63° 40 mA
53	61° 39 mA	60° 38 mA	60° 36 mA

Table 3 A.M. (Normal Subject)

Rise/Fall Times (sec)

Frequency (Hz)	.5/1	4/2	8/3
25	38° 40 mA	56° 41 mA	58° 41 mA
35	64° 42 mA	62° 42 mA	63° 41 mA
45	72° 41 mA	73° 41 mA	72° 40 mA
53	54° 40 mA	58° 39 mA	58° 39 mA

Table 4 K.R. (Normal Subject)

Rise/Fall Times (sec)

Frequency (Hz)	.5/1	4/2	8/3
25	62° 51 mA	60° 51 mA	61° 51 mA
35	61° 50 mA	61° 50 mA	61° 50 mA
45	62° 50 mA	60° 50 mA	62° 49 mA
53	61° 48 mA	62° 48 mA	62° 49 mA

Table 5 D.S. (CP Subject)

Rise/Fall Times (sec)

Frequency (Hz)	.5/1	4/2	8/3
35	75° 40 mA	75° 40 mA	75° 40 mA
45	70° 39 mA	70° 40 mA	72° 38 mA
48	65° 40 mA	60° 40 mA	60° 39 mA
53	85° 40 mA	80° 39 mA	75° 40 mA

Table 6 C.R. (CP Subject - Unaffected Arm)

Rise/Fall Times (sec)

Frequency (Hz)	.5/1	4/2	8/3
25	57° 49 mA	72° 49 mA	70° 49 mA
35	77° 43 mA	78° 42 mA	77° 42 mA
45	74° 42 mA	75° 41 mA	75° 42 mA
53	74° 40 mA	75° 40 mA	75° 41 mA

Table 7 C.R. (CP Subject - Affected Arm Before FES Program)

	Rise/Fall Times (sec)		
Frequency (Hz)	.5/1	4/2	8/3
25	-22° 42 mA	-15° 42 mA	-20° 42 mA
35	-7° 42 mA	-10° 41 mA	0° 43 mA
45	-12° 41 mA	-10° 42 mA	-5° 43 mA
53	-2° 39 mA	0° 40 mA	-7° 40 mA

Table 8 C.R. (CP Subject - Affected Arm After 16 Weeks in FES Program)

	Rise/Fall Times (sec)		
Frequency (Hz)	.5/1	4/2	8/3
25	60° 44 mA	60° 46 mA	60° 46 mA
35	73° 48 mA	71° 47 mA	68° 45 mA
45	74° 44 mA	75° 46 mA	76° 45 mA
53	79° 43 mA	80° 44 mA	78° 44 mA

is the markedly decreased dependence of the response on the rise/fall time. The largest standard deviation for the three ramping times at a given frequency is 2.5°, approximately the uncertainty in measuring. For some of the frequencies the shortest rise/fall time even corresponds with the best response.

Clearly, no patterns or fundamental relationships can be established with a CP sample size of two. Each individual should be tested in order to find the customized parameter settings which work best for him. Unfortunately, many children would not have the patience, tolerance, or understanding for this procedure. In these circumstances starting stimulation values must be culled from prior experience. A frequency around 53 Hz with a rise/fall time on the order of 4/2 seconds seem to be reasonable values for stimulation of the distal, upper extremity.

5.2 CP Subjects Involved with this Research

5.2.1 Medical History

Three boys participated in this study. All three exhibited spastic hemiplegia. Each attends his local, public school and is in the grade considered normal for his age.

D.S., now 13 years old, has been involved with an FES program through OSU since December, 1990 [7]. Before the initiation of the electrical treatment physical complications on the left side of his body resulting from CP included weak or absent ankle dorsiflexion, spastic wrist flexion, and a cortical thumb. A breech baby, he was not diagnosed as having cerebral palsy until the age of 12. The FES therapy administered by Mozelewski through May, 1991 was previously outlined.

C.R. is a 16 year-old with involvement of the right half of his body. Along with ankle extensor and wrist flexor hypertonia he exhibited some dystonia. Attempted voluntary movement of his hand, thumb, or fingers increased the spasticity of the muscles antagonistic to the motion as well as produced slow, twisting movements in opposition to the desired action. Anxiety heightened this effect. He was a breech and a Caesarean section had to be performed at birth. A physician diagnosed his CP at 9 months. He was given physical therapy in which he was made to perform such tasks as picking up blocks and riding a tricycle from 14 months of age until age three or four. C.R. wore an orthotic wrist brace for the three months before he began the stimulation for this study. He did not like the brace because the hard plastic hindered hand function and, therefore, discontinued its use when the FES program began.

A 9 year-old boy, M.E. is also affected on the right side of his body. He displayed dropfoot and a hyperflexed wrist. He was also bothered by seizures which sometimes lasted for hours. Born 14 weeks prematurely, he was a breech delivered at home by paramedics. They had to use CPR to sustain him until he could be rushed to the hospital. Cerebral palsy most likely arose from intracranial bleeding. M.E. began working with a physical therapist when he was 18 months old and continued until age six. He wore a thumb orthosis for part of this time. During the last three years of this period the treatment was really not very intense. From age six to the present time he has been participating in an hour of therapy per day at school.

The goal in each case was to improve voluntary functional use of the disabled upper limb. Therapy entailed using electrical stimulation to create essential movements, such as wrist and thumb extension, that the boy was originally unable to do well on his own. Ideally, FES would reduce spasticity, increase the strength of the agonists, and initiate the development of a new, undamaged neural pathway to the brain. The focus was on bettering the grasp-and-release and pinching motions. Stimulation programs were tailored to meet the special needs of each boy.

5.3 D.S.

As noted, D.S. had undergone 18 weeks of electrical stimulation of his extensor carpi ulnaris muscle prior to the beginning of this thesis project. By the end of that period his wrist extension had increased to the point where he was able to raise his hand to an angle 56° above the plane of his forearm. He was actively helping to extend his wrist against the resistance imposed by a 3.5 lb. weight placed around his fingers.

This ability to place his wrist in a more mechanically advantageous position did bring improvement in functional performance as substantiated by an increase in grip strength and the acquisition of the ability to wash his hair by himself. He still, however, was hampered by a cortical thumb that hindered his pinching and grasping motions. It was felt that increasing the range of motion of the thumb would help in these areas. Thus, D.S. underwent a program of electrical stimulation to try to better thumb abduction and extension, as well as to continue to improve wrist extension.

5.3.1. Treatment

The following muscles were targeted for excitation: the abductor pollicis brevis for thumb abduction, the extensors pollicis longus and brevis for thumb extension, and the extensor carpi ulnaris for wrist extension. Figures 13 and 14 depict the locations of these muscle groups and the corresponding electrode positions. Approximate electrode placement, based on some anatomical knowledge and some experimentation on a normal subject, was chosen to coincide with sites where the muscles ran close to the skin. Exact electrode locations for D.S. were then determined by some trial-and-error in the vicinity of the spots corresponding to the aforementioned areas. The employment of volume conduction through surface electrodes inevitably resulted in some spillover excitation of neighboring muscle groups. A criterion for electrode placement was the minimization of undesired movement resulting from the spread. Better electrical contact was formed by placing a layer of electrode gel between the electrode and the skin. The electrodes were held in place with tape.

Electrical excitation of the wrist extensors had been continued since the end of the prior study. The first three weeks of therapy for this study consisted solely of stimulating the wrist extensor. D.S. worked to help the stimulation in raising his wrist against the resistance provided by a 3.5 lb. weight. After three weeks thumb extension was added. Thumb and wrist extension were produced concurrently during the stimulation sessions, which took place 5 days per week for 30 minutes per session. A few weeks later FES was also applied to the thumb abductor muscle.

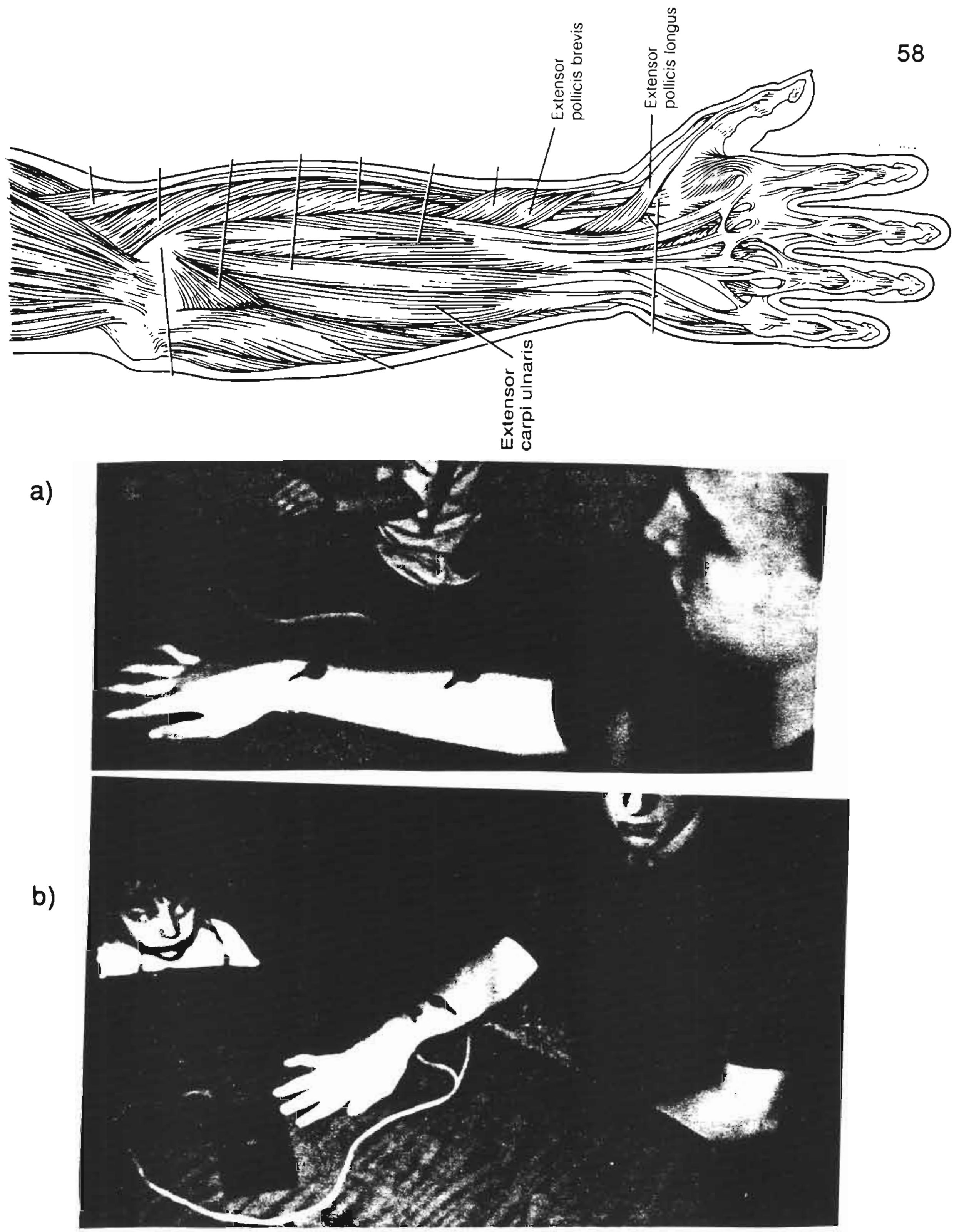
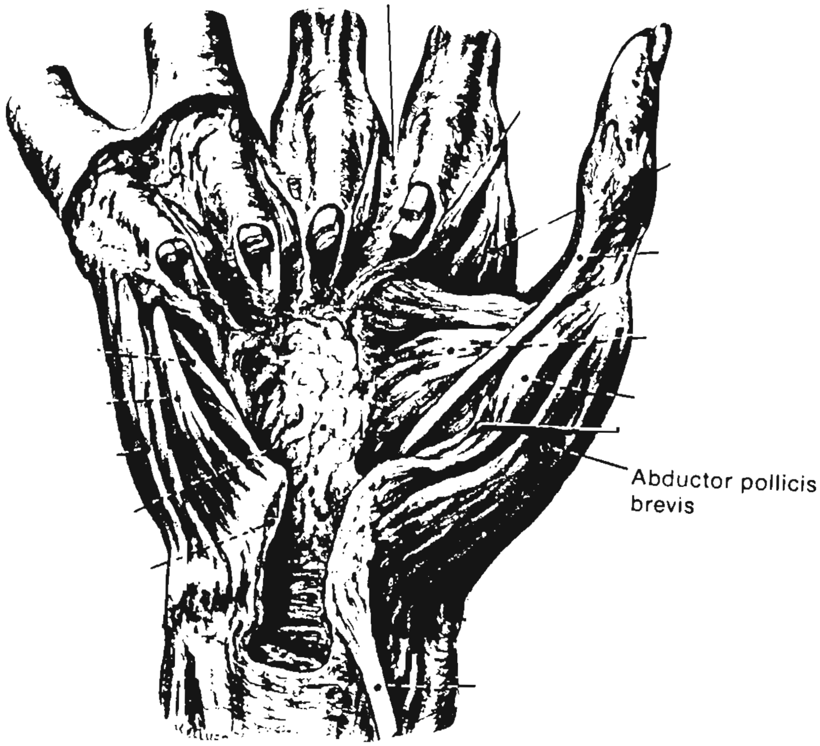


Figure 13 Anatomical location of the thumb extensors and ulnar wrist extensor [49] and the electrode placement for a) wrist extension and b) thumb extension

a)



b)

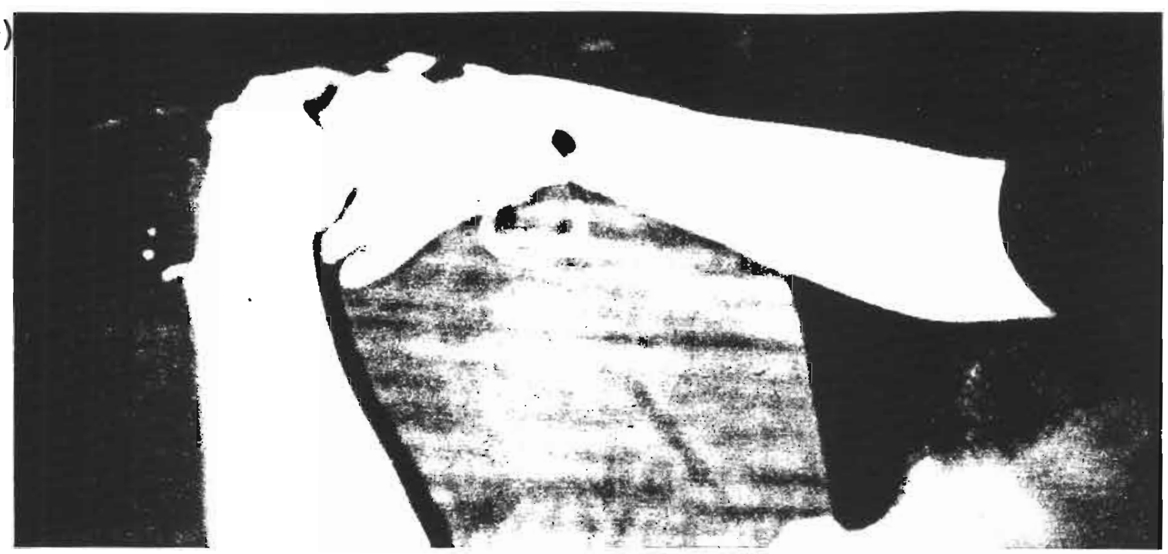


Figure 14 a)Anatomical location of the abductor pollicis brevis [50] and b)the electrode placement for thumb abduction

The parameters set in the other study, 48 Hz and .5/1 sec. rise/fall time were used until testing was done again in October (see table 5.) At that time 53 Hz and a .5/1 sec. ramping produced the best response and the settings were changed accordingly.

The 3.5 lb. weight which had been employed prevented thumb extension, so its use was ended. In its place Theraband® was wrapped around the four fingers and tied to a chair to provide the desired resistance. Later this material was also tied around the thumb and first finger in an attempt to strengthen the thumb muscles responsible for extension and abduction.

D.S. encountered problems in trying to maintain good contact with the electrode on the abductor pollicis brevis. Due to CP he could not generate much supination, so stimulation had to be performed with his palm facing down. Gravity and the folding of the skin during contraction worked against the tape and the electrode sometimes fell off. To overcome this difficulty an electrode was sewn into a golf glove. The glove kept the electrode in good contact with the skin.

It was decided to try and have a sleeve constructed with all the electrodes D.S. needed for the upper limb sewn into it after reading an article describing an electrode garment for the leg [51]. The spandex sleeve containing the electrodes for wrist extension and thumb abduction, extension, and opposition was designed and made by a branch of Hanger Orthopedics Corporation in Columbus. The sleeve was not finished until the end of this research. A picture of it is shown in figure 15.

By October wrist extension had increased to such an extent that it was on a par with or even slightly better than that in the

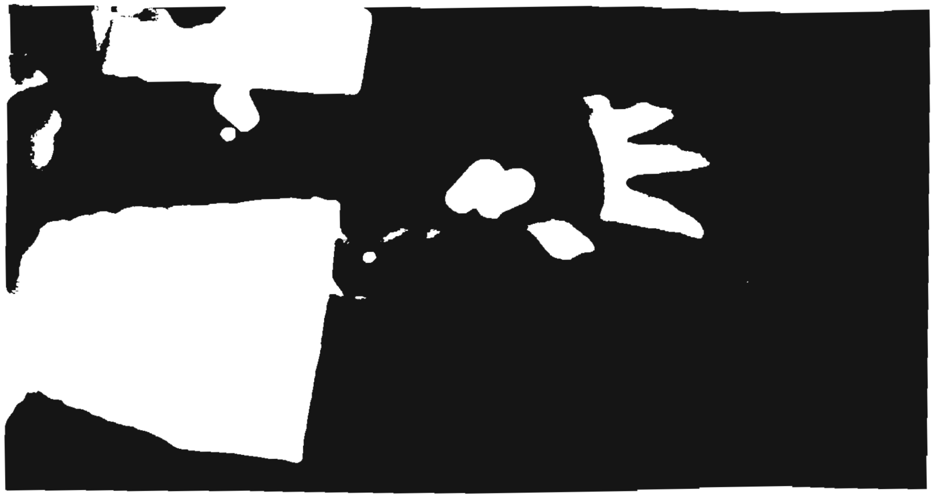


Figure 15 Electrode sleeve from Hanger Orthopedics

unaffected hand. At this point it was decided to discontinue electrical stimulation of the extensor carpi ulnaris. D.S. did continue to exercise the wrist just as he had done with the stimulation. Wrist extension and thumb extension and abduction were all performed synchronously. The concurrent thumb extension did spill over to cause a little wrist extension, but this was no more than 15° whereas he was able to voluntarily extend his wrist 90°. Unfortunately, he sprained his wrist in early January. At that time stimulation of the wrist extensor was begun again. A log of the treatment program is listed in table 9.

5.3.2 Measurements

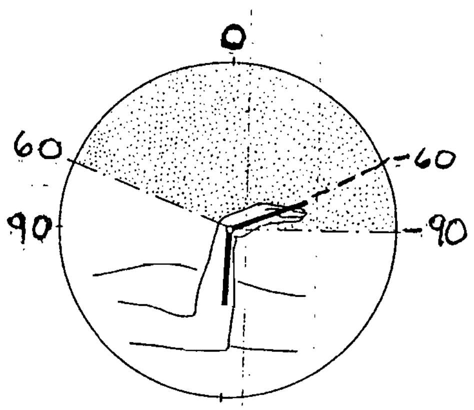
Measurements were taken periodically in an effort to quantitatively document the state of hand functionality throughout the course of the program. Voluntary range of motion of the wrist and the thumb were assessed with a goniometer. For the wrist the angle recorded was the one formed by the side of the palm of the hand and the plane of the forearm. The plane of the forearm marked

Table 9 D.S. FES Program

Date	Activity
5/18 - 6/7	Stimulated wrist extension with 3.5 lb. weight for 30 min. per session, 5 days per week. Settings: 48 Hz, 0.5/1 sec. rise/fall.
6/8 - 7/2	Simultaneous wrist and thumb extension. No weights. Thumb extensor stimulation increases gradually from min. to 30 min. per session by 6/18.
7/3 - 7/24	Wrist and thumb extension with 3.5 lb. weight: 30 min. Thumb abductor stimulated separately: 15 min.
7/26 - 8/30	Wrist and thumb extension against blue Theraband: 30 minutes. Thumb abduction against yellow Theraband: 15 min.
8/31 - 10/13	Wrist extension and thumb extension, blue Theraband: 30 min. Thumb abduction with golf glove and yellow Theraband: 20 min.
10/14	Change frequency setting to 53 Hz
10/23	Stop stimulation of wrist extensors. Continue to perform wrist extension exercises while concomitantly stimulating thumb extensors and abductor: 30 min.
11/13	Change size of ground electrode.
12/20 - 1/9	Use Theraband every other stimulation session.
1/10	Sprained wrist.
1/11- 1/16	No stimulation or exercises.
1/17 - 2/1	Stimulate wrist and thumb extensors : 30 min. Stimulate thumb abductor separately: 20 min.

0° extension; the angle became increasingly positive as the metacarpals were raised above this plane (see figure 16.) The thumb extension angle was formed be the phalanges of the first finger and the proximal phalanx of the thumb with the apex at the thumb carpometacarpal joint. The angle was in a plane parallel to that of the palm. Thumb abduction was measured in a plane perpendicular to that of the palm. The phalanges of the first finger and the proximal phalanx of the thumb again constituted the rays of the angle; the apex was located on the metacarpal of the thumb (figure 16 .)

a)



b)

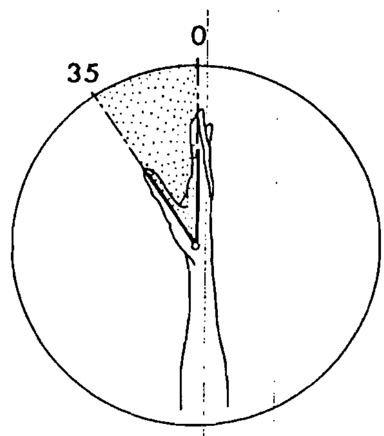


Figure 16 Measuring a) wrist extension and b) thumb abduction [52]

Grip strength was assessed using a JAMAR hand dynamometer, model 5030J1. As the study was conducted over a considerable length of time it became necessary, unfortunately, to change dynamometers. The second gauge was identical in model, manufacturer, and appearance to the first, but it was new.

D.S. used both dynamometers on two different testing sessions to check for any variance in calibration between the two. The results are examined in the next chapter.

Lateral and palmer pinch strength were tested with a pinch gauge, model #PG-30, made by B&L Engineering. A swap of outwardly identically pinch gauges was also made during the course of this study. As with the dynamometers comparisons were made on two different days.

These force measurements provided data on possible changes in strength caused by alterations in the ability to place the wrist and digits in more mechanically advantageous positions. They did not directly address changes in the muscles undergoing stimulation. In order to examine the effects of FES on the wrist extensor muscles themselves D.S. was periodically tested with a Cybex II®. This device records the torque generated during contractions at specified, constant velocities. The machine regulates the velocity at which a contraction can occur by varying the resistance against which one must work in flexing and extending the wrist.

Tasks were developed as a basis for quantifying changes in hand dexterity. Four of the six tests were modifications of procedures which others had used to evaluate hand function [53,54]. The time necessary for completion was recorded for each task. Important criteria for the tasks were that they require the use of only one hand, could be performed in a short period of time (at least in normal subjects), and use easily attainable, pòrtable, and inexpensive materials.

Two of the tests called for lifting a container approximately three inches above a table in order to set it atop a box, releasing the container, and then lowering it back to the table. Repetition of this sequence three times constituted a single timed trial. The object used in one of the tasks was a soup can, cylindrically shaped with a height of 10 cm and a diameter of 6.6 cm and weighing 10.75 oz. The subject had to complete the sequence with a filled plastic cylinder weighing 2.625 oz and measuring 10.3 cm in height and 4.3 cm in diameter for the other evaluation. The participant was allowed to grasp the cylinders from the top. These tests were designed to test the strength and motion of grasping and releasing. In the future one should use three similar cans for each test rather than repeating the movement three times with the same can; sometimes the trials had to be rerun because the subject failed to fully release the object.

Another evaluation of dexterity involved having D.S. pick five playing cards one at a time from the top of a deck of cards and turn them over. This required a palmer pinching motion as well as either wrist movement or supination depending on which way D.S. chose to flip the card. Supination was a problem which was not specifically addressed, but which was seemingly helped by the improvement of other muscle actions.

The task proving to be the most difficult was to remove a quarter, dime, nickel, and penny one at a time from a 9"x13"x2" metal pan without pulling the coins up the side of the pan. Three of each of these denominations of currency were placed in the pan before the start of every trial. The retrieval of the dime,especially, required rather fine control of the thumb and/or fingers.

The other two tasks were created based on thoughts about what movements would provide good monitoring of improvement in CP children in particular. One called for picking up 5 pens out of a 6.75"x3.5"x1.375" cardboard box and placing them into a cup of height 13.2 cm which had an opening of diameter 9.5 cm. The narrowness of the box forced the employment of a palmer pinching motion to lift the pens. The other task involved the subject removing five rubber balls with 2.2 cm diameters from a 9"x13"x2" pan. The evaluation with the balls was developed much later than the other tests. Its derivation stemmed from observations about the difficulty in picking up the coins. Progress in hand manipulation could be subjectively seen without any corresponding change in the time needed to retrieve the coins because the currency was so thin. Thus, the test with the balls was instituted.

In an effort to evaluate the strength of the thumb extension and abduction a type of simple spring scale was developed. However, it proved to be too dependent on the range of the motion of the thumb and too unreliable.

5.4 C.R.

5.4.1 Treatment

The biggest initial concerns of C.R. were his inability to extend his wrist and the accompanying severe extension of his fingers when trying to raise his wrist (see figure 17.)

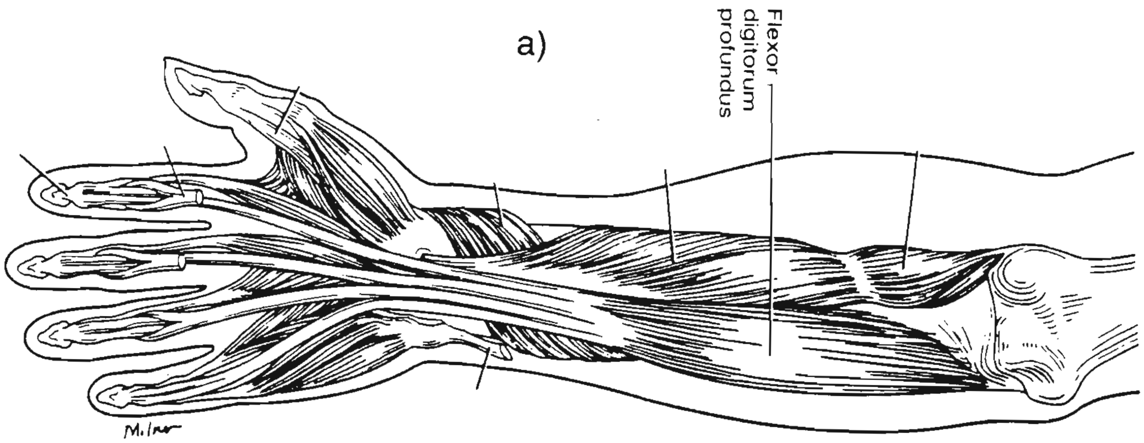
Figure 17 C.R. wrist extension - 8/27

Accordingly, the first course of action was to stimulate his extensor carpi ulnaris. Strong wrist extension naturally produces finger flexion, so this excitation addressed both problems.

The search to find favorable values for the frequency and rise/fall times was enumerated in section 5.1.5 and the results are listed in table 7. The preferred combination was 53 Hz with 4/2 second ramping. During the first weeks of the stimulation the on time was periodically increased and the off time decreased until a ratio of 20 sec/8 sec was reached. An attempt to further lower the rest period seemed to fail to provide sufficient time for the muscle to fully relax between contractions and therefore was abandoned in favor of the settings just described.

Later, efforts were made to reduce the difficulties C.R. was having when attempting to use his thumb. The voluntary range of motion of his thumb was always fairly good, but he experienced problems when trying to incorporate the thumb into a conscious motion. He used the first two fingers as pincers, in fact, in lieu of the first finger and the thumb, when he wanted to pick up objects before he began the FES program. Thus, the extensors pollicis longus and brevis along with the abductor pollicis brevis were artificially excited. The wrist and thumb extensors were stimulated simultaneously for 30 minutes per day for 5 days out of each week. Thumb abduction was generated separately for 15 minutes at each FES session. Also, as of the middle of December the flexor digitorum superficialis and, probably, profundus were stimulated along with the thumb abductor in the hope of producing better finger flexion to aid in the palmer pinching motion. See figure 18 for the muscle location and corresponding electrode placement.

a)



b)

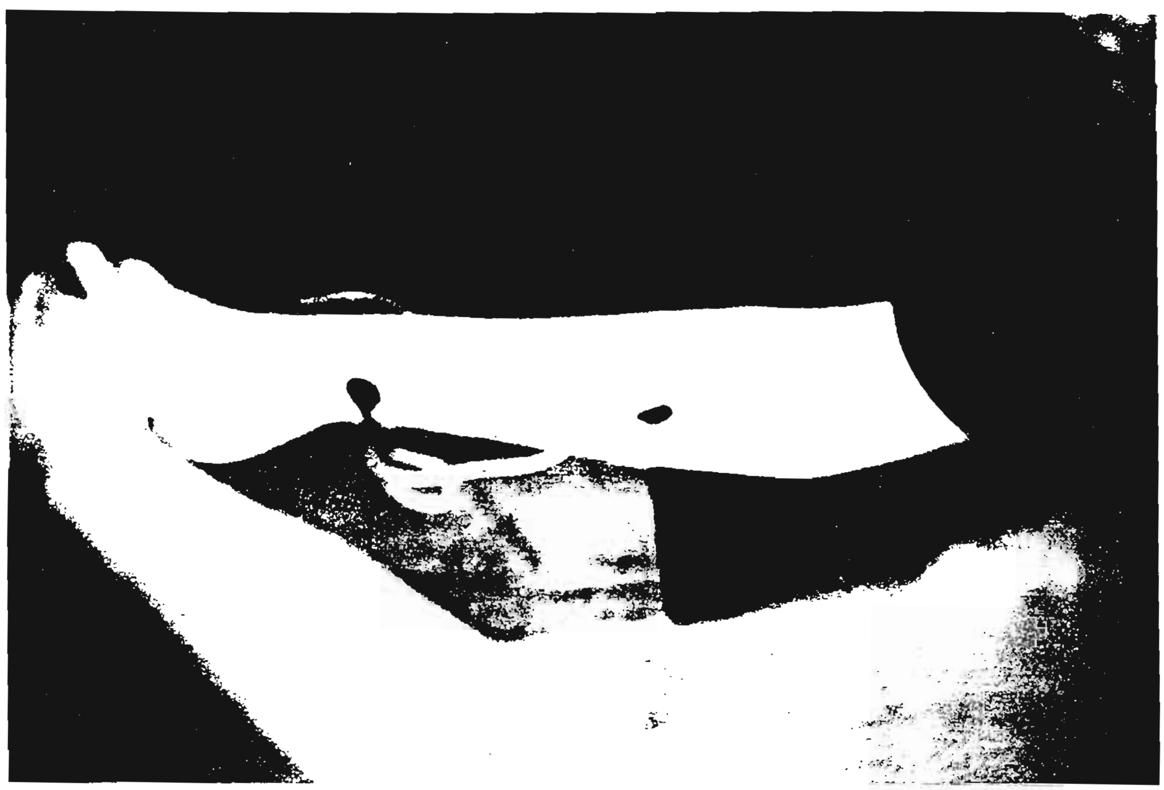


Figure 18 a)Anatomical location of the flexor digitorum profundus [49] and b)the electrode placement to produce finger flexion

The thumb abductor was initially excited at a level to generate the maximum possible response. However, it was observed over a few weeks of testing that this actually corresponded with a worsening of function. After the amplitude was reduced his performance improved. A causal relationship cannot be proven, but the correlation is very suggestive.

As his hand was big enough to fit it, a 1 lb. weight was eventually wrapped around his hand to provide resistance to his wrist extension exercises. By the end of this study he had worked up to half-an-hour of wrist extension with the weight concomitant with the thumb extension. A log of C.R.'s FES program may be found in table 10.

5.4.2 Measurements

Measurements were taken weekly, except for a three week period coinciding with holidays. The closer proximity of his home to the OSU campus afforded more frequent examinations than were performed with the other two subjects. Evaluations of thumb and wrist range of motions were made on two dates prior to the beginning of the FES program.

Thumb and wrist range of motions were quantified with the use of a goniometer. As with D.S. grip strength was assessed with the JAMAR hand dynamometer. Once again, due to difficulties in obtaining the use of a gauge, different dynamometers were used. The device made by Lafayette was employed for three sessions. On two other occasions strength was tested with a gauge made by Stoelting Co. Trials on and after 10/29 were performed with the JAMAR. Comparisons were conducted on 2/4 using all three instruments. The gauges are shaped differently, so calibration testing would not provide the needed information; C.R. had to use all three on one date to properly compare them.

Table 10 **C.R. FES Program**

Date	Activity
9/29 - 10/6	Wrist extensor stimulation: 20 min. per session, 5 days per week. 10 sec. on, 10 sec. off. 53 Hz, 4/2 sec. rise/fall
10/8 - 10/13	10 sec. on, 10 sec. off: 30 min.
10/14 - 10/28	15 sec. on, 7 sec. off: 30 min.
10/29 - 11/2	20 sec. on, 4 sec. off: 30 min.
11/3 - 11/10	20 sec. on, 8 sec. off (these settings are maintained for rest of program): 30 min.
11/11 - 11/18	Wrist and thumb extensor stimulation: 30 min.
11/19 - 12/7	Wrist and thumb extension: 30 min. Thumb abduction: 15 min.
12/8 - 12/14	Wrist and thumb extension with 1 lb. weight: 15 min. Reduced amplitude for thumb abductor stimulation.
12/16 - 12/31	Wrist and thumb extension with 1 lb. weight: 20 min. Thumb abduction and finger flexion: 15 min.
1/1 - 1/6	Wrist and thumb extension with 1 lb. weight: 25 min. Thumb abduction and finger flexion: 15 min.
1/13 - 2/3	Wrist and thumb extension with 1 lb. weight: 30 min. Thumb abduction and finger flexion: 15 min.

An instrument to measure lateral and palmer pinch strength became available a few weeks into the FES program. It was the same gauge made by B&L Engineering as mentioned before. This instrument was used in all the assessments.

At each testing date after the start of the FES treatment C.R. performed multiple trials of three of the six dexterity tests previously described. The tasks involving the coins, the five pens, and the five balls were used. It was observed during work with D.S. that these three manual manipulations produced the most noticeable differentiation between the results with the disabled and uninvolved hands. One modification was made; the metal pan holding the coins and balls was replaced with a 9"x11"x3.25" cardboard box which helped to discourage the pulling of the objects up the sides.

5.5 M.E.

5.5.1 Treatment

Being only mildly affected by CP in his extremities, M.E. had much better hand function than the other two boys even before he began the FES therapy. The primary goals with M.E. were to increase the range of motion and strength of his wrist. The range of motion of his thumb was already quite good. His ability to control his thumb and fingers before beginning FES was fairly good as well. Figure 19 illustrates his ability to grasp a pen using lateral pinch before beginning the stimulation program.

The key issue was whether M.E., being much younger than C.R. and D.S., would tolerate the stimulation. He did not have the patience for a search of the parameter space as was conducted with the other two subjects. The frequency and rise/fall times were set to 53 Hz

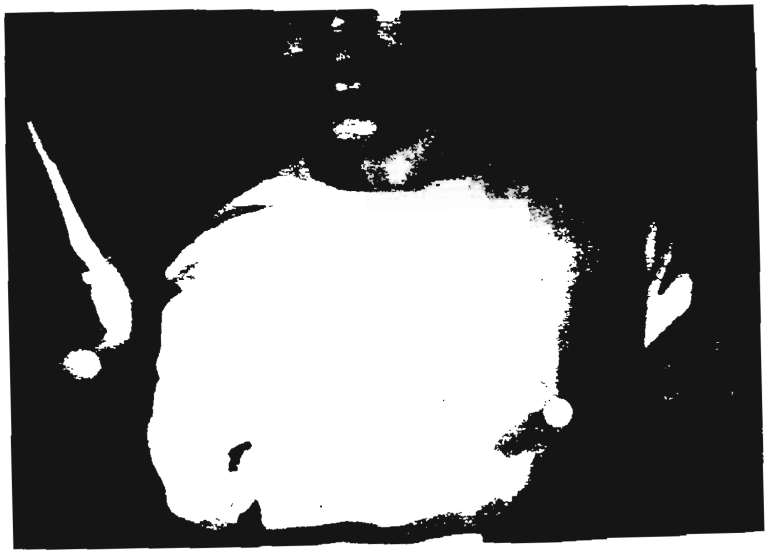


Figure 19 M.E. lateral pinch before beginning FES - 10/6

and 4/2 sec based on prior experience. Fortunately, he handled the FES quite well. The on/off ratio was gradually increased until reaching 23 seconds on and 7 seconds off.

The stimulation time of the extensor carpi ulnaris was also increased over time to 30 minutes per day, 5 days per week. Theraband® was introduced to aid in strengthening as his hands were too small to support weights. The hope was to work the muscle to fatigue. The Theraband® helped quicken the onset of fatigue while still permitting the full possible range of motion. A summary of stimulation program is listed in table 11.

5.5.2 Measurements

Assessments of M.E.'s wrist and thumb range of motions were made on three separate dates prior to the start of the FES program. The retrieving of the coins and of the pens in tests identical to those performed by C.R. were timed on two of these occasions. Grip strength was measured on one of these dates.

After the advent of the use of the electrical therapy on M.E., testing sessions were held approximately once every two weeks. One date had to be cancelled because M.E. was having trouble with seizures.

Wrist extension, thumb extension, and thumb abduction were measured with a goniometer. Grip strength was again assessed with a hand dynamometer. The JAMAR model was used exclusively after 11/2. Twice prior to that day the Stoelting device was employed. M.E. tried both gauges in one session and calibrations between the two were made accordingly. The instrument made by Lafayette was used for one of the baseline evaluations, but it was later determined that the grip span had been set such that it was too wide for M.E., so the measurements had to be discounted.

Lateral and palmer pinch strengths were assessed with the pinch gauge made by B&L Engineering. The same gauge was used for all the measurements. Dexterity was quantified via the same three tasks used with C.R.

Table 11 **M.E. FES Program**

Date	Activity
10/13 - 10/16	Wrist extensor stimulation: 10 min. per session, 5 sessions per week. 8 sec. on, 12 sec. off; 53 Hz, 4/2 sec. rise/fall.
10/17 - 10/23	8 sec. on, 12 sec. off: 15 min.
10/24 - 10/28	14 sec. on, 7 sec. off: 15 min.
10/28 - 11/4	2 X 15 min./ day; 5 days per week.
11/5 - 11/20	1 X 30 min./ day; 5 days per week.
11/21 - 1/9	23 sec on, 7 sec. off (final settings) : 30 min.
1/10 - 2/2	Wrist extension against yellow Theraband: 30 min.

CHAPTER VI
DATA

6.1 Display Method

All of the measurements taken for this research assessed voluntary performance. No stimulation was used during any of the testing. The three boys differed from each other in terms of age and type and severity of cerebral palsy and underwent different FES therapy accordingly. Thus, the data for each subject was analyzed separately. A copy of all the data collected on each examination date for each boy is listed in Appendix A.

No use of control subjects was possible. The subjects definitely knew whether or not they were actually receiving electrical stimulation, so no type of "placebo" control group could be employed. The probability of finding volunteers willing to try to extend their wrists and thumbs for half-an-hour every day without receiving any FES is undoubtedly quite small. Even if one did locate such volunteers, they could not serve as a true control group because the participants would not acquire the visual and proprioceptive feedback afforded by the movement produced by electrical stimulation. Possibly, in the future, researchers may try to produce movement in CP patients solely through mechanical means and compare the results to those obtained with electrical stimulation.

For this study the primary control was provided by the subject himself in testing done before the stimulation program was started.

The slope characterizing improvement over time after the start of the stimulation program was compared to the slope describing improvement before the beginning of FES. Unfortunately, for a number of the evaluations no measurements were obtained prior to the introduction of electrical stimulation. Another caveat exists: there is no guarantee that the CP subject would not have gotten better on his own without the stimulation and that improvement just happened to coincide with the FES therapy.

In some instances the subject's uninvolved side served as the control for the affected side. This is not strictly valid as the two sides might naturally change quite independently of each other. Still, comparison of relative improvement in the involved and uninvolved limbs can provide a rough measure of advances generated solely by the stimulation program. The comparison was especially useful in ascertaining the effects of learning through practice and repetition in regard to the dexterity tasks.

The primary objective of recording the data was not so much to examine the absolute values as to look for trends which might occur during the FES programs. The main concern was to determine whether an FES program could produce quantifiable improvement in voluntary function, not if some arbitrary level of "normalcy" could be attained. Scatterplots for each type of test for each boy in the study were drawn in order to make the trends more easily discernible.

Performance in a person with spastic CP can vary widely through the course of time. The degree of spasticity itself will fluctuate from day to day and even within a single day. The amount of voluntary control that can be exercised over the musculature can change from trial to trial as the cerebral palsy subject struggles to overcome the hypertonia and primitive reflex patterns. Therefore, multiple trials of a given type of evaluation were generally run. To aid in instances where the variability obscured possible trends regression analysis was used to determine if any statistically significant patterns existed. The full regression analyses which were performed can be found in Appendix B. The scatterplots and summaries of the statistical tests follow this section.

6.2 D.S.

6.2.1 Range of Motion

D.S.'s peak voluntary thumb extension and thumb abduction were measured on two separate days before any direct stimulation of the thumb was begun. Wrist extensor FES was being applied during the three week period between the baseline measurements, but thumb extension was actually worse on the second testing date. Thumb abduction had increased slightly by the second session, but it remained relatively unchanged throughout the course of the program anyway. The baseline measurements were grouped together on day 0 of the scatterplots in figure 20. Day 1 in both plots demarks 6/7, the first day of electrical excitation of the thumb extensor muscles.

The scatterplot for the range of thumb extension documents steady improvement until levelling off after day 140 at approximately 12°. This value represents a 35° increase over the mean of the two baseline angle recordings. On the other hand, the thumb abduction plot shows no trend at all. No significant change occurred in the maximum voluntary thumb abduction.

The dramatic increase in wrist extension D.S. experienced in the prior study, [7], has already been described. Figure 21 reveals that

```
MTB > plot c19 vs. c18
a)
                             D.S. - Left Thumb Extension
            -
          15+                            * *      2 *
            -                            *
    ltexta  -                 *       2   *    *   *         2
            -              *              *    *
            -                 *              2
           0+
   Angle    -
            -
            -
            -
         -15+ *    *
            -
            -          *
            -
            -
         -30+ *
              +---------+---------+---------+---------+---------+------ltextd
              0        50       100       150       200       250
                                           Days
MTB > plot c31 vs. c30
                             D.S. - Left Thumb Abduction
        35.0+                             *
            -
    ltabda  - *
            -                             2
            -                                                 *
        30.0+          *       *                  2           *
            -
            - *               *       *
   Angle    -      *                     *      *
            -
b)      25.0+              *          * *      *   *
            -
            -
            -                                2
            -
        20.0+                                      *
            -
              +---------+---------+---------+---------+---------+------ltabdd
              0        50       100       150       200       250
                                           Days
```

Figure 20 D.S. Scatterplots of a) left thumb extension and b) left thumb abduction

```
MTB > plot c41 vs. c40     D.S. - Left Wrist Extension
          -                             2       *
          -
        90+                          *  *       *   2
          -                                                      2
 lwexta   -                          *     2 2
          -                                *  *     *
          -                                         *
        75+            *
          -                *
          -      *         *
 Angle    -
          -
        60+
          -
          -
          -       *
          -
           --------+---------+---------+---------+---------+--------lwextd
                  80       120       160       200       240
                                       Days
```

Figure 21 D.S. left wrist extension

this improvement continued until D.S. reached the physical limit, imposed by the ligaments and joints, of this motion in his affected limb. At this 90° extension he had greater voluntary extension with his left wrist than with his unaffected, right wrist. Left wrist extension remained at this level even after the stimulation of the extensor carpi ulnaris was discontinued after day 126.

6.2.2 Grip and Pinch Strengths

No baseline measurements of grip or pinch force were taken since the subject had already been receiving FES for the wrist extensor for 18 weeks before beginning this study. The six examination sessions from the prior study showed that grip strength and lateral and palmer pinch force had all increased during the 18 weeks [7].

Figure 22 displays the left-hand grip and lateral pinch strength data for this research. Day 1 represents the day of 5/17.

Evaluations were originally performed with the same hand dynamometer and pinch gauge used in the prior study. However, during the FES program it became necessary to switch these instruments for newer gauges of the exactly same make and model. D.S. used both sets of instruments on two different testing sessions to check for differences in calibration. Enough time was allocated between trials to prevent any effects from fatigue.

In both sessions the mean grip force in the right hand as measured with the newer dynamometer was four lbs., or 6%, greater than that recorded with the older dynamometer. Yet, the variability between trials for a given date with a given gauge was as high as 10 lbs. On the earlier of the dates the mean left hand grip force measured with the newer gauge was 5 lbs., or 16%, higher than that graded with the older instrument. However, on the next occasion the two means were identical. Evaluations performed with a normal subject yielded almost identical results with the two dynamometers.

Some of the data gathered with the newer pinch gauge was slightly higher in comparison to that collected with the older instrument while other measurements were higher when taken with the older gauge. All the measurements for a given pinch were well within the variability that D.S. exhibited within multiple trials of a single strength test recorded with a single gauge on a given day.

One would ideally put both sets of instruments under a press which displays applied stress and thereby precisely compare them. The older gauges could not be taken to do this. The two pairs of devices did, though, seem to be calibrated very closely.

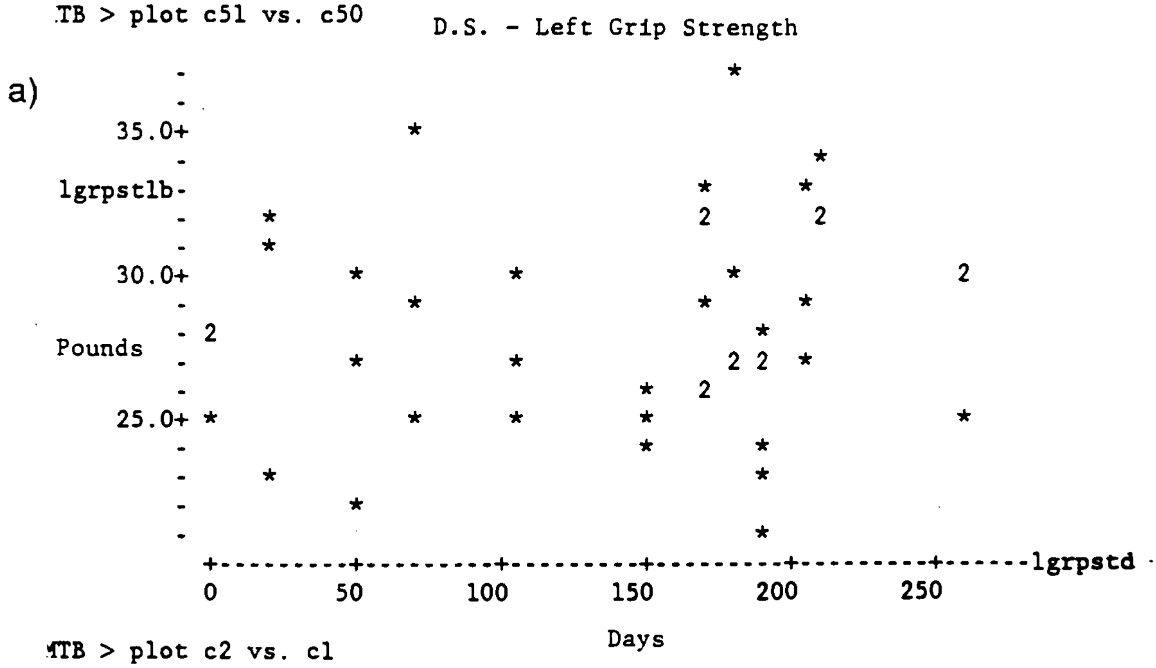
As can be seen in figure 22, no patterns over time can be discerned for either the left grip strength or lateral pinch strength; the fact that the R^2-values for both sets of data are less than 2% strongly bears out the observation that no linear trends exist. The corresponding regression results for the right side are very similar to the left-hand results.

On the testing dates before 8/31, the 84th day after the start of stimulation of the thumb extensors, D.S. was unable to perform the palmer pinch motion correctly. He had to curl the tip of his thumb under the pinch gauge and press with the side of his thumb. For the palmer pinch evaluations on and after 8/31 D.S. was able to put his thumb in the proper position to push with the pad of his thumb. The only data in the scatterplot of left palmer pinch strength in figure 23 is that taken on and after 8/31. A log transformation of the data was performed to help linearize the plot . The regression analysis of the log(strength) fitted a line with a positive slope to the data. The slope was significant at a p-value of .062.

6.2.3 Dexterity Tests

D.S. often exhibited considerable fluctuations in the time required to complete a given task, especially in the early part of this research. The variability generally tended to decrease during the course of the stimulation study. While a sign of progress, this led to problems with heteroscedasticity, a violation of one of the basic assumptions which must be valid in order to use regression. Log transformations of the times to completion were taken in order to reduce heteroscedasticity without obliterating any linear trends

.TB > plot c51 vs. c50



MTB > plot c2 vs. c1

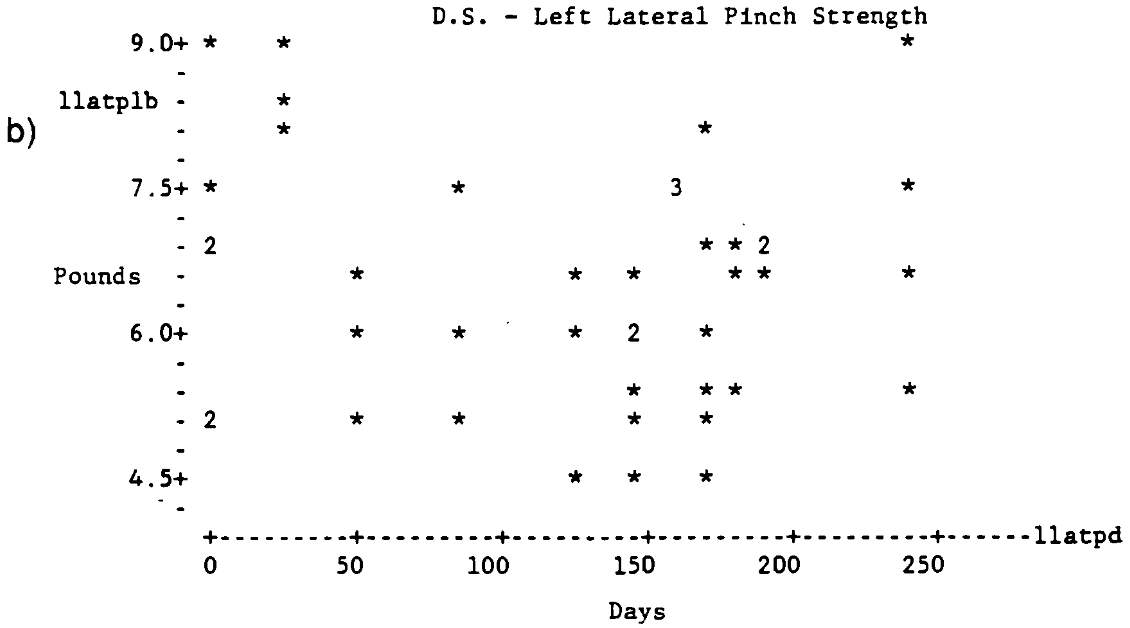


Figure 22 D.S. left hand strength: a) grip and b) lateral pinch

a)

```
   IB > plot c11 vs. c10
                              D.S. - Left Palmer Pinch Strength
          -                                    2
          -
       6.0+
          -
  lppstlb -                                                       *
          -                                    * *
          -
       4.5+
          -
   Pounds -   *                    2           *
          -                                      2                *
          -
       3.0+   *             2      3      5    *                  2
          -
          -   *                    *   2  *
          -                 *          *
          -
            ----+---------+---------+---------+---------+---------+--lppstd
               90       120       150       180       210       240
                                         Days
```

b)

```
  MTB > plot c15 vs. c10

          -
  log(pps)-                                    2
          -
          -                                                       *
      1.60+                                    * *
          -
          -
          -   *                    2           *
          -                                      2                *
      1.20+
          -   *             2      3      5    *                  2
          -
          -
          -   *                    *   2  *
      0.80+
          -                 *          *
          -
            ----+---------+---------+---------+---------+---------+--lppstd
               90       120       150       180       210       240
                                         Days
```

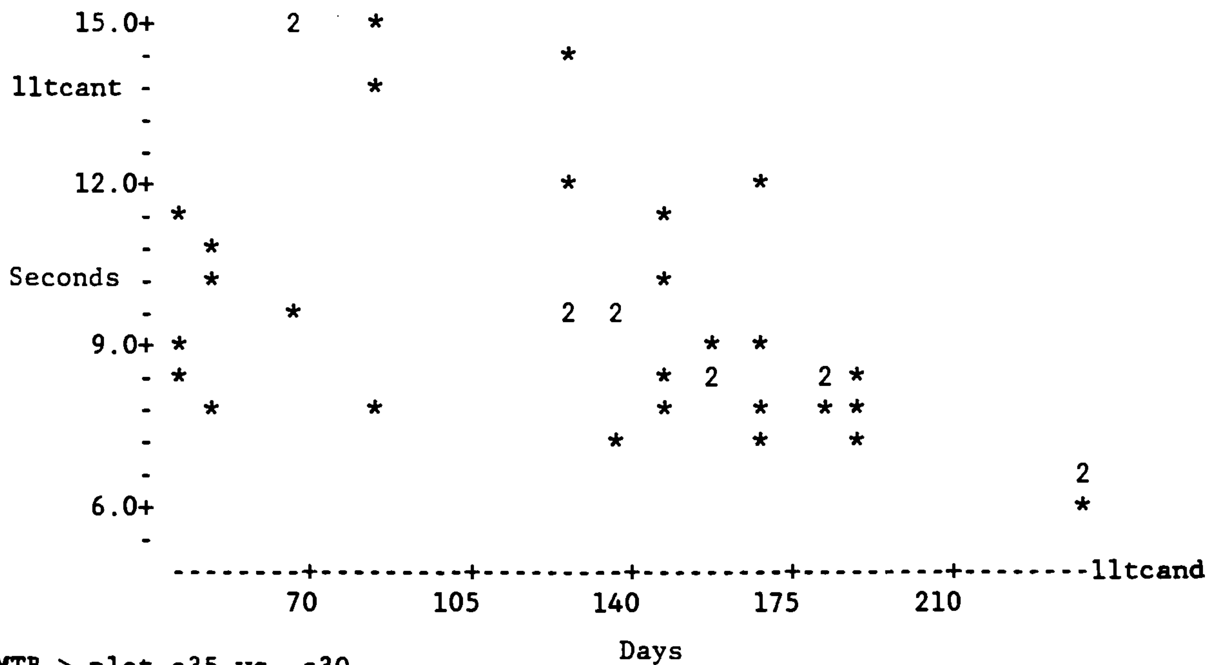
Figure 23 D.S. left a) palmer pinch strength and b) log transformation which may have been present in the original data. The dexterity tests were first administered 43 days after FES was begun on the thumb. However, dramatic improvement in the scores did not take place until at least 80 days after 6/7. Figures 24-28 contain the scatterplots for the tests involving the lighter can, heavier can, pens, coins, and playing cards and the accompanying log transformations.

The regression analyses for these five tasks revealed that the decreases in time as a function of number of days in the FES program are strongly, statistically significant. Lines with negative slopes were fitted to the data for these five dexterity measures. T-tests for all of the five negative slopes showed the slopes to be significant for a p-value less than .001. When using ANOVA, the F-tests yielded the same results. The lowest R^2-value was 35.6%, that for lifting the lighter can. This was the easiest task for D.S. to perform on the first day the dexterity assessments were run. The other R^2-values are as follows: 57.4% for lifting the heavier can, 47.9% for picking up the pens and placing them in the cup, 48.0% for turning over the playing cards,and 53% for picking up the coins.

The task entailing picking five balls out of a box was not instituted until day 137. Regression analysis of the data concerning the balls did not find any trend. However, figure 29 shows that a downward trend exists except for the final day of testing. Removal of the data for 2/1 yields a statistically significant slope with regression. D.S. performed well in all the other tasks on that date; perhaps he just lost motivation when it came to picking up the balls, the final test of the day.

MTB > plot c31 vs. c30

D.S. - Lifting Lighter Can - Left Hand



MTB > plot c35 vs. c30

Log Transformation

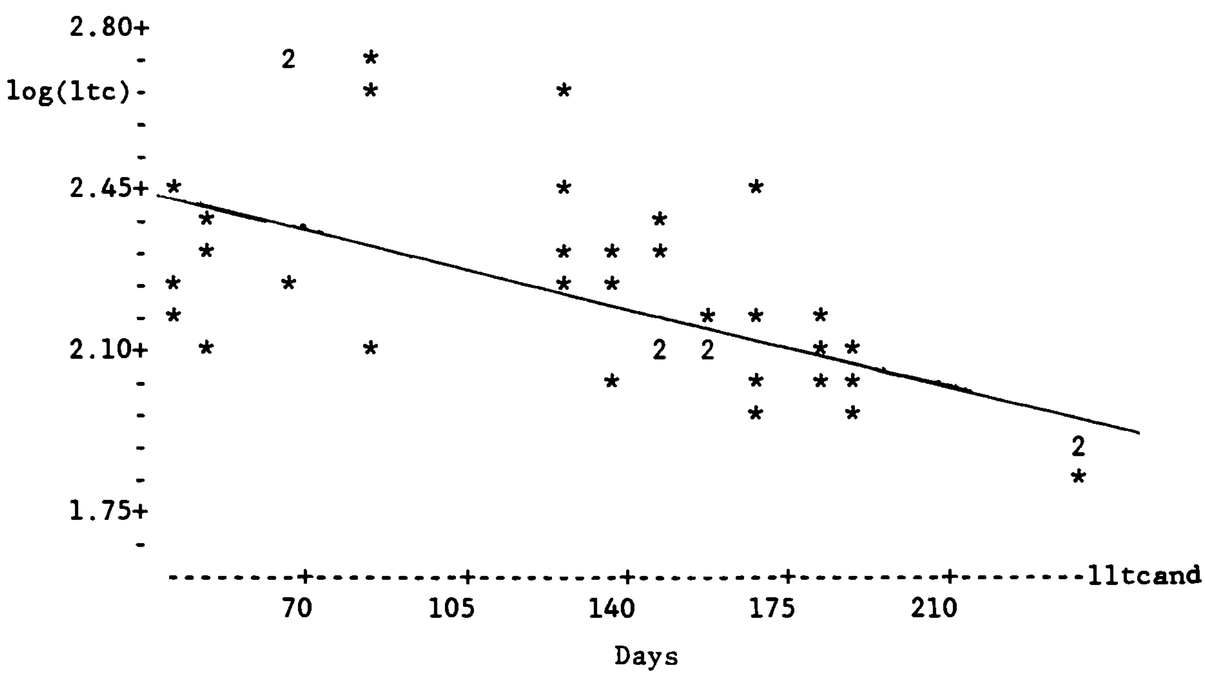


Figure 24 D.S. lifting lighter can with left hand

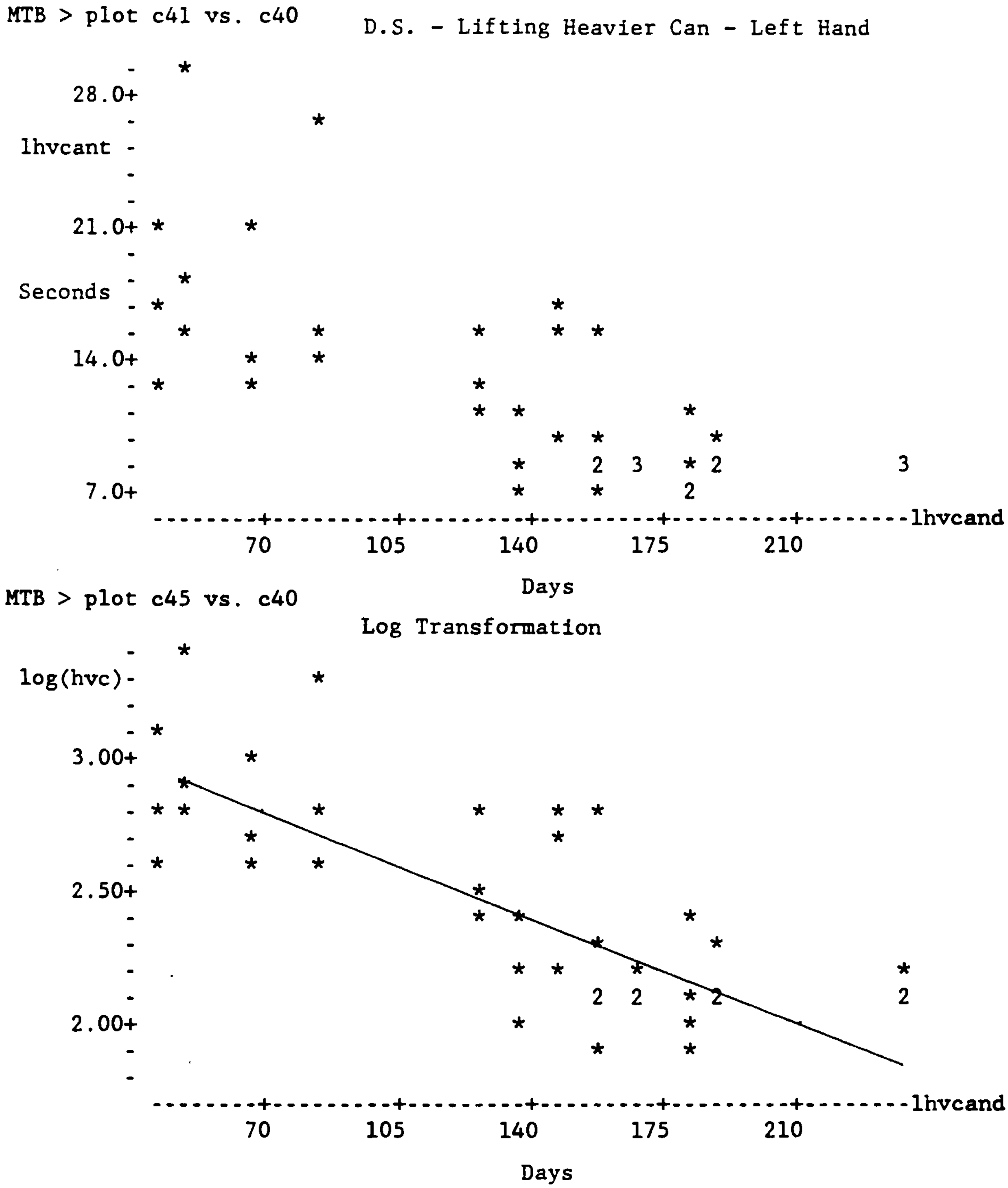
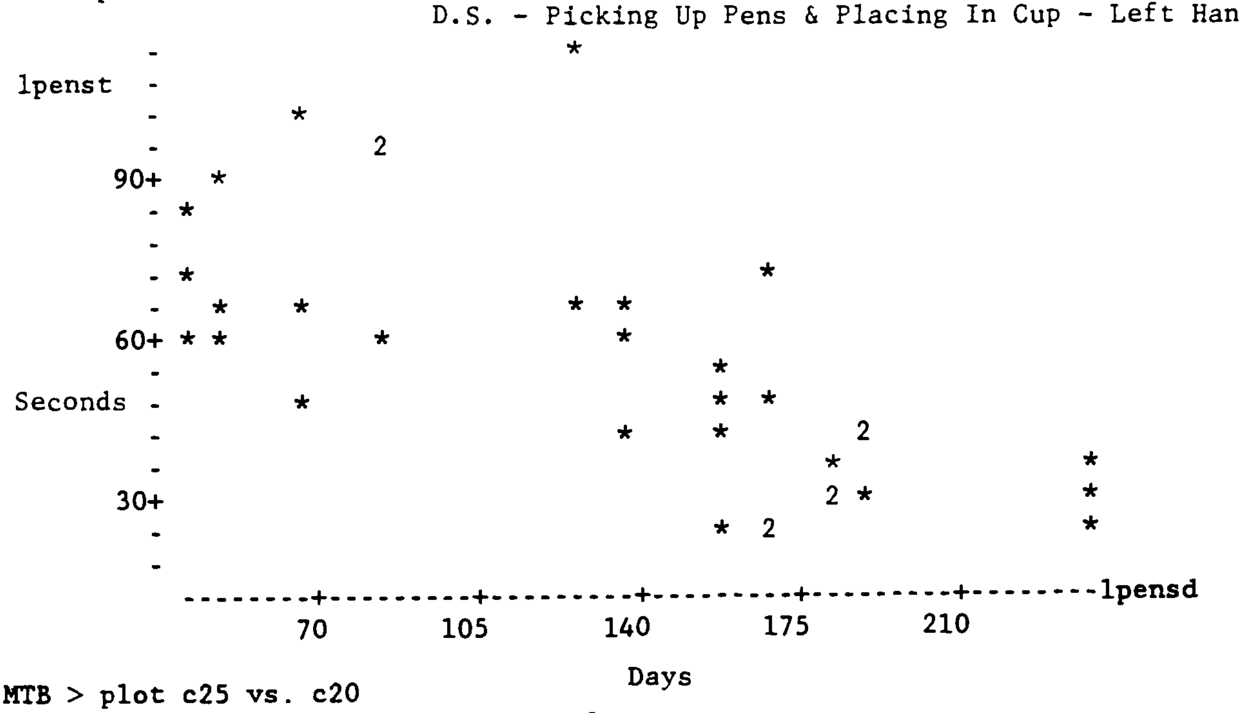


Figure 25 D.S. lifting heavier can with left hand

MTB > plot c21 vs. c20



MTB > plot c25 vs. c20

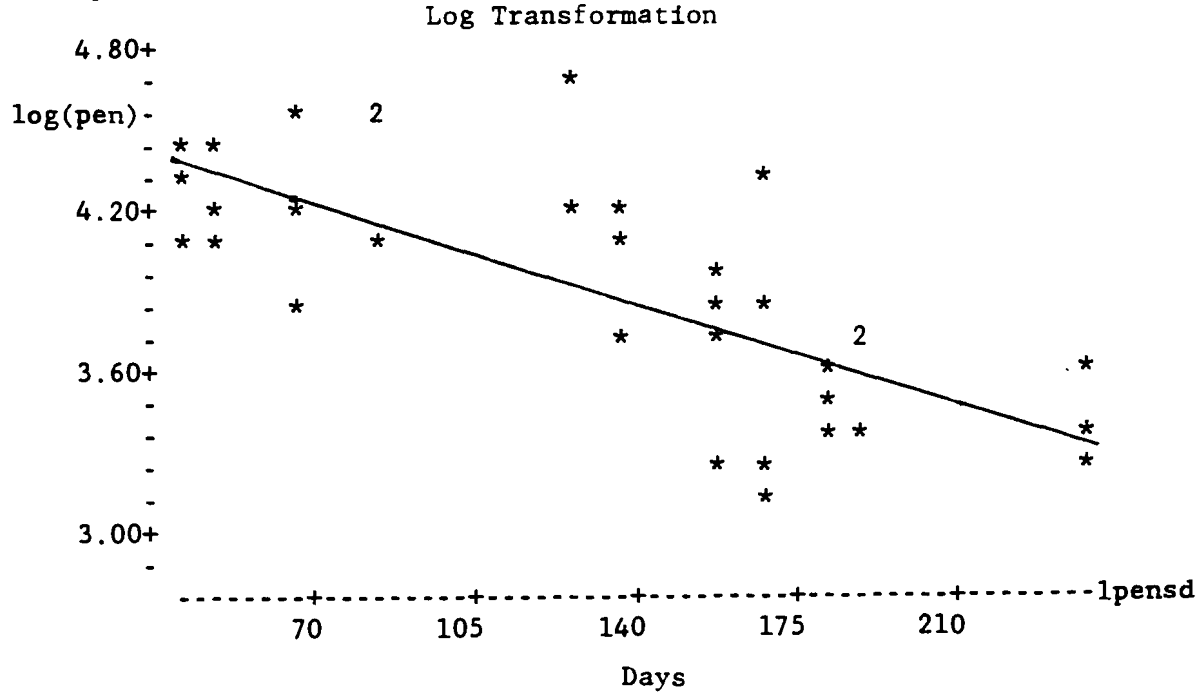
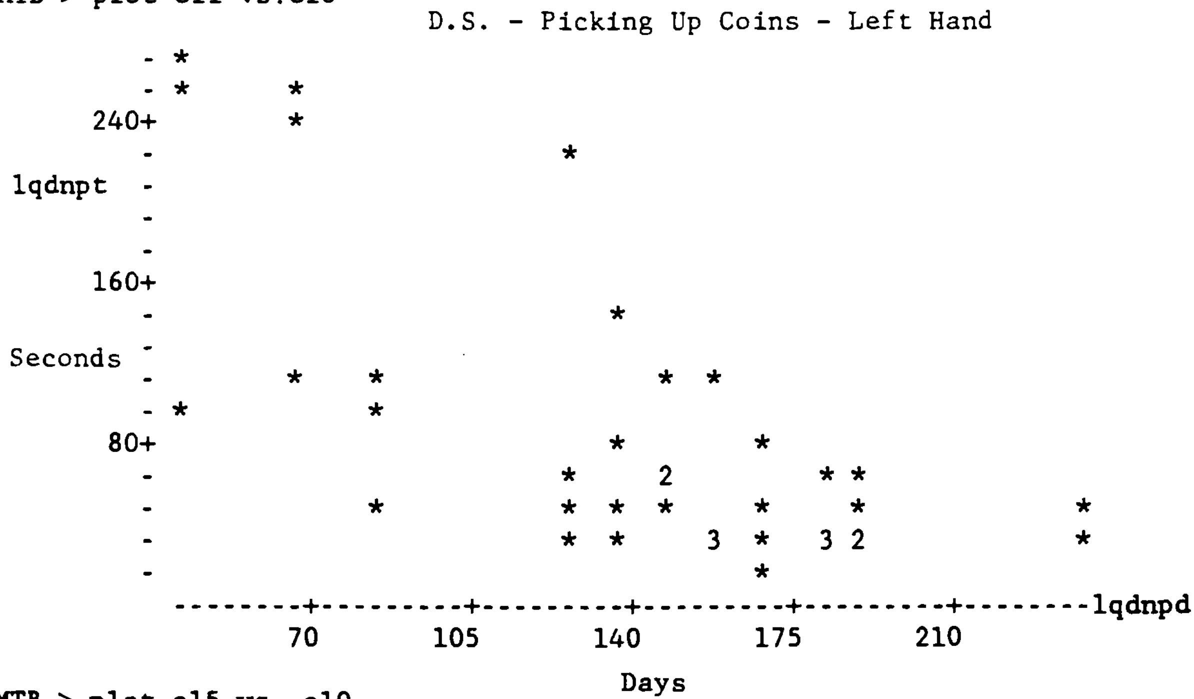


Figure 26 D.S. picking up pens with left hand

MTB > plot c11 vs.c10



MTB > plot c15 vs. c10

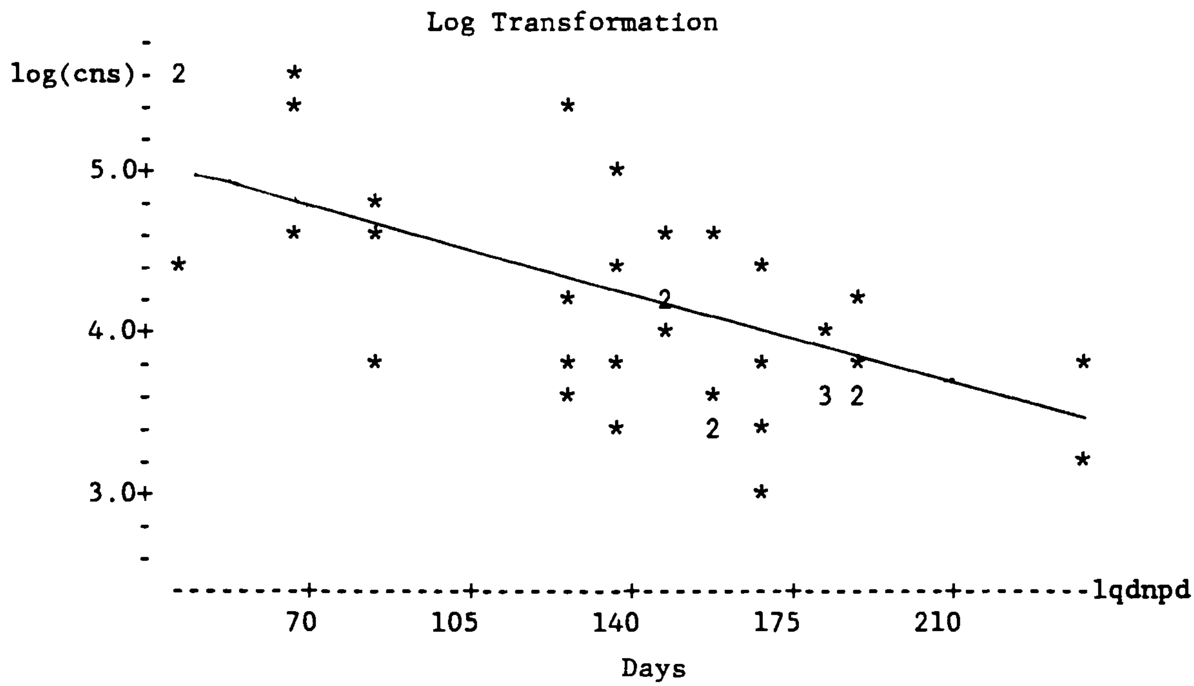
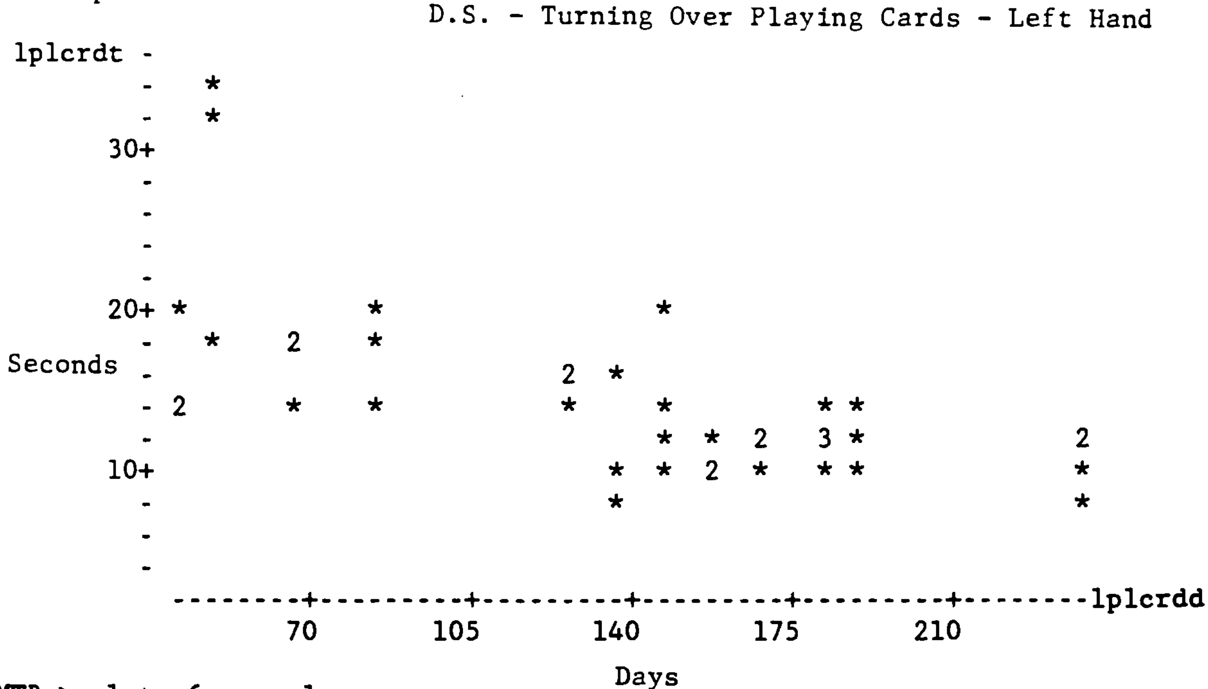


Figure 27 D.S. picking up coins with left hand

MTB > plot c2 vs. cl



MTB > plot c6 vs. cl

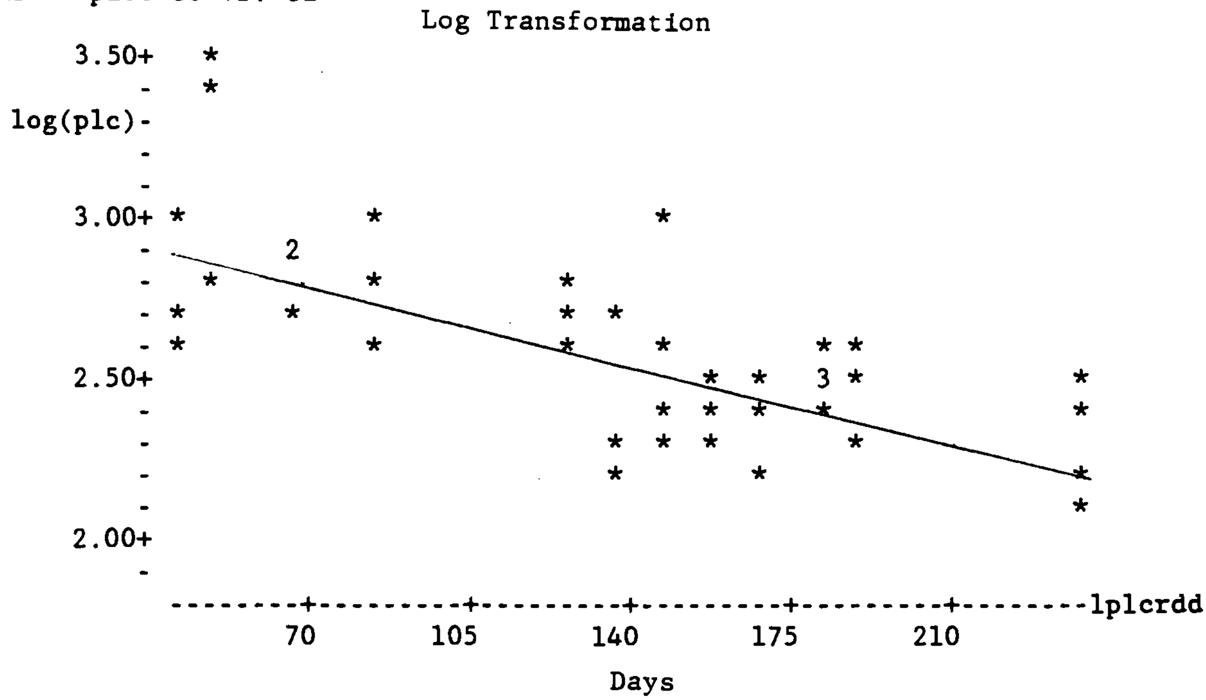


Figure 28 D.S. turning over playing cards with left hand

```
MTB > plot c56 vs. c55
                                D.S. - Picking Up Balls - Left Hand

        -
    28.0+         *
        -
15ballt -
        -
        -
    21.0+                                                      *
Seconds -    *
        -              2
        -         *         *                                  *
        -    *         *                                       *
    14.0+                                 *
        -         *         *         *                        2
        -                   *      2  2
        -         *
        -
     7.0+                                     *
          ----+---------+---------+---------+---------+---------+--15balld
            140       160       180       200       220       240
                                      Days
```

Figure 29 D.S. picking up balls with left hand

Regressions performed on the data for the right hand fitted lines with statistically significant downward slopes. The scatterplots are shown in figures 30-32. The decreases recorded with the left hand were much greater than those seen with the right hand. For example, the mean for picking up the pens with the right hand dropped from 6.4 sec. for the first two examination sessions to 5.2 sec. for the last two for a 19% decrease. Over the same period the left hand mean time fell from 72.4 sec. to 34.2 sec. for a 53% decrease. In picking up the coins the time fell from 8.0 to 4.6 for the right hand and from 207.4 to 41.2 for the left. This represents a 42% drop for the right handed times and an 80% reduction for the times of the involved hand.

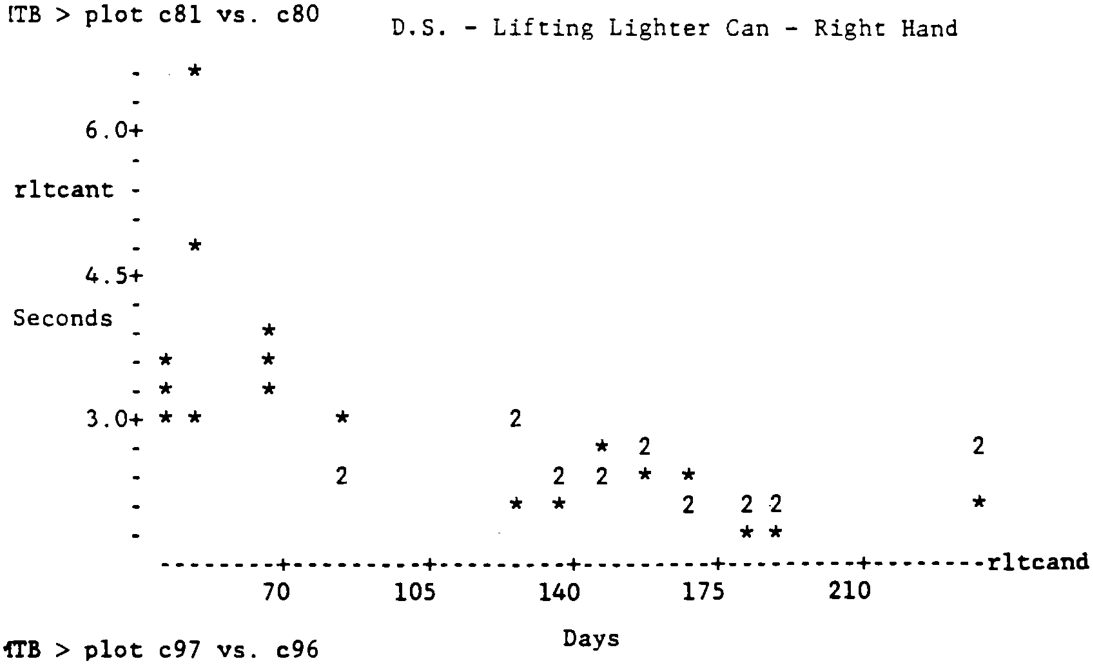
6.2.4 Cybex

The Cybex data for a given day consists of three sets of wrist extensions and flexions at seven different velocities for each hand. The peak torque generated by D.S. was recorded for each extension and flexion. Means and standard deviations were calculated at each velocity. All of the data from the Cybex is listed in Appendix A.

Unfortunately, the Cybex calibration was not checked on the first two testing dates. The machine was calibrated for all subsequent measurements. One can see from the tables in Appendix A that the mean right hand torque for a given velocity is quite constant over four consecutive examination dates for which the Cybex was definitely reading the same. All four values lie within 10% of each other at every speed. Thus, the values from the uninvolved limb were used as a rough measure of calibration to lessen the effects of possible changes not only in the machine, but also in motivation and

MTB > plot c81 vs. c80

a)



MTB > plot c97 vs. c96

b)

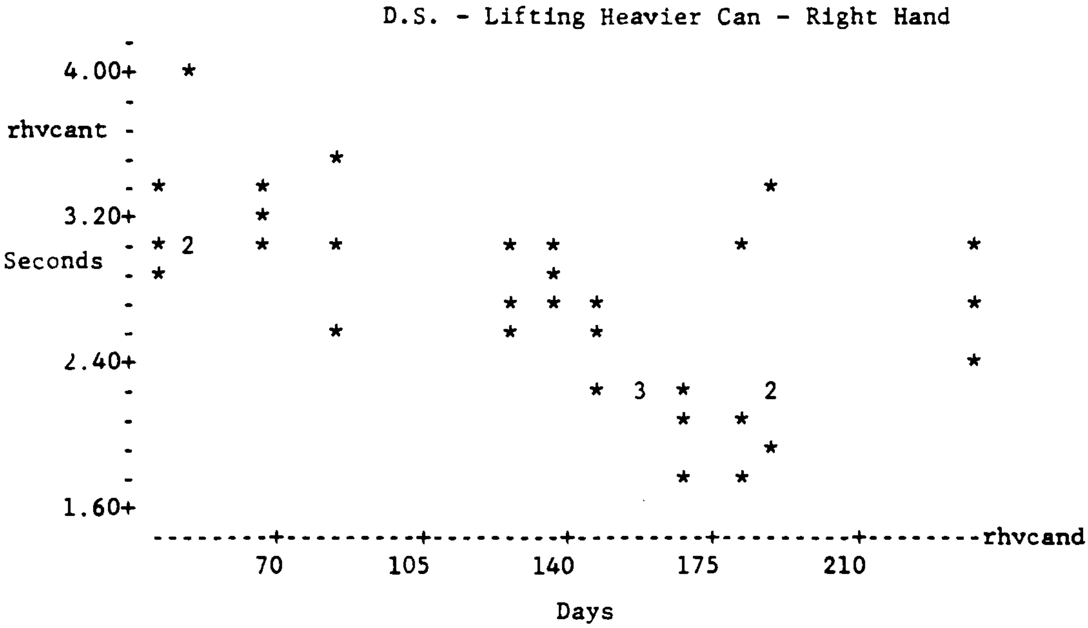
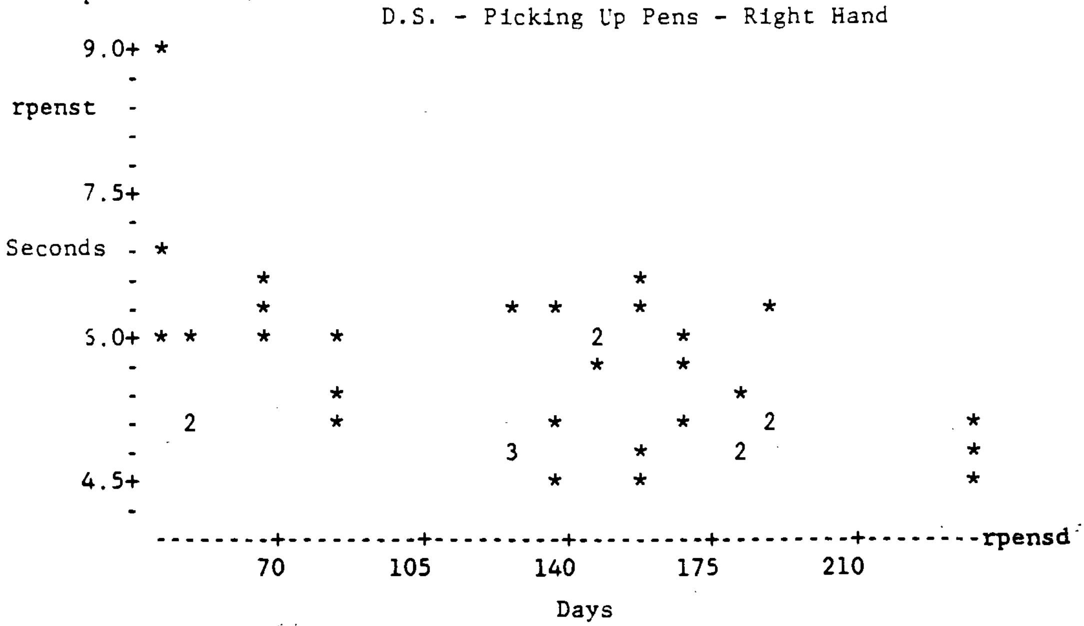


Figure 30 D.S. - right hand lifting containers a) lighter b) heavier

MTB > plot c71 vs. c70

a)



b)

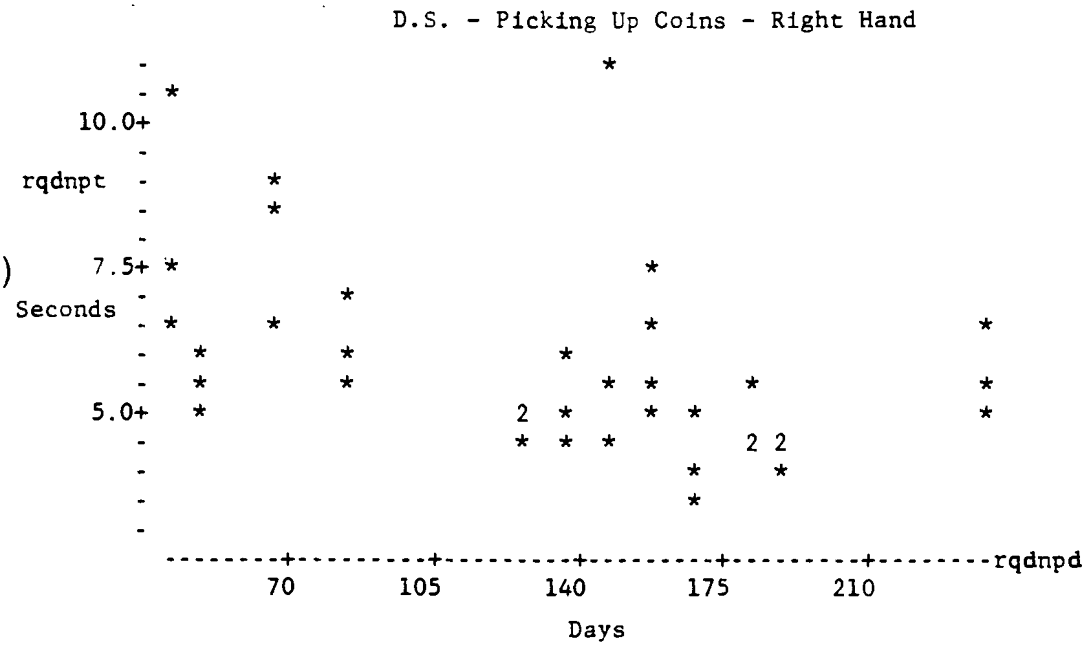


Figure 30 D.S. - right hand picking up a) pens and b) coins

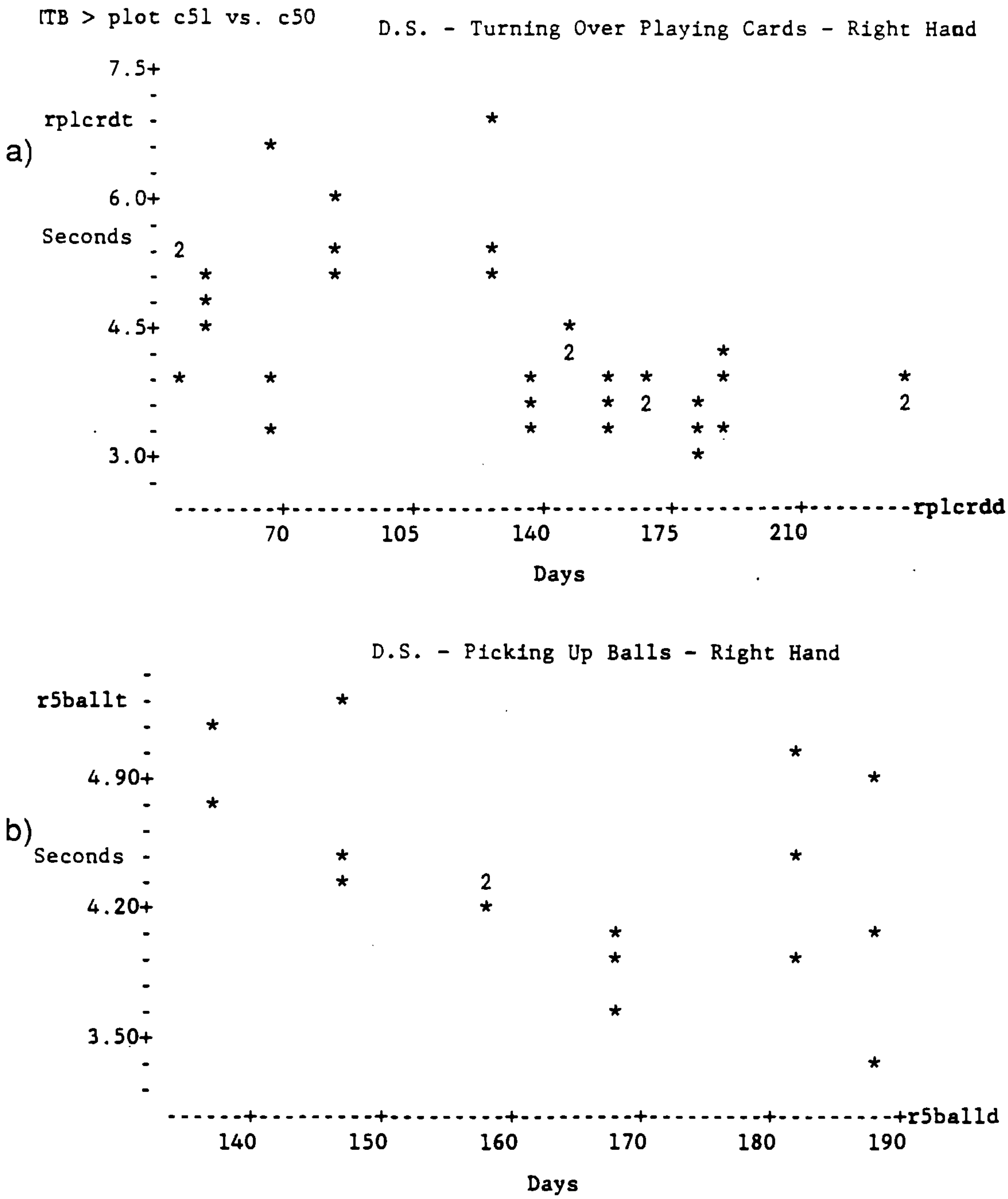


Figure 32 D.S. - right hand a) turning over playing cards and b) picking up balls

health. The mean torques for the left wrist were divided by the corresponding values for the right side and the ratios were plotted for each testing session vs. the velocity of the contraction. Due to the variability inherent to CP subjects the three peak torques produced by the three extensor contractions at a single velocity were averaged. Figure 33 consists of the data taken before stimulation of the wrist extensor was ended. Figure 34 shows the results of the last two sessions before and the two testing dates after the end of stimulation.

When analyzing the Cybex data from normals, the general practice is to use the highest torque value from three contractions at a single velocity rather than to average the three contractions. Plots for each testing date of the ratios of the single highest recordings at a given speed appear in Appendix B. The overall shapes of the curves are quite similar to those in figures 33 and 34.

6.3 C.R.

6.3.1 Range of Motion

The baseline measurements for thumb extension and thumb abduction reveal that C.R. already had pretty good thumb range of motion before beginning the FES program; a voluntary extension of 80° and abduction of 40° were recorded. One week after the stimulation started the thumb abduction jumped to approximately 80° and remained in the 70-80 degree range for the rest of the time except for two sessions, one in which the mean dipped to 48° and the other in which it fell to 35°. The week after both of these dates the thumb abduction was back up to its 80°-level. Peak thumb extension remained quite constant; it never fell below 65°.

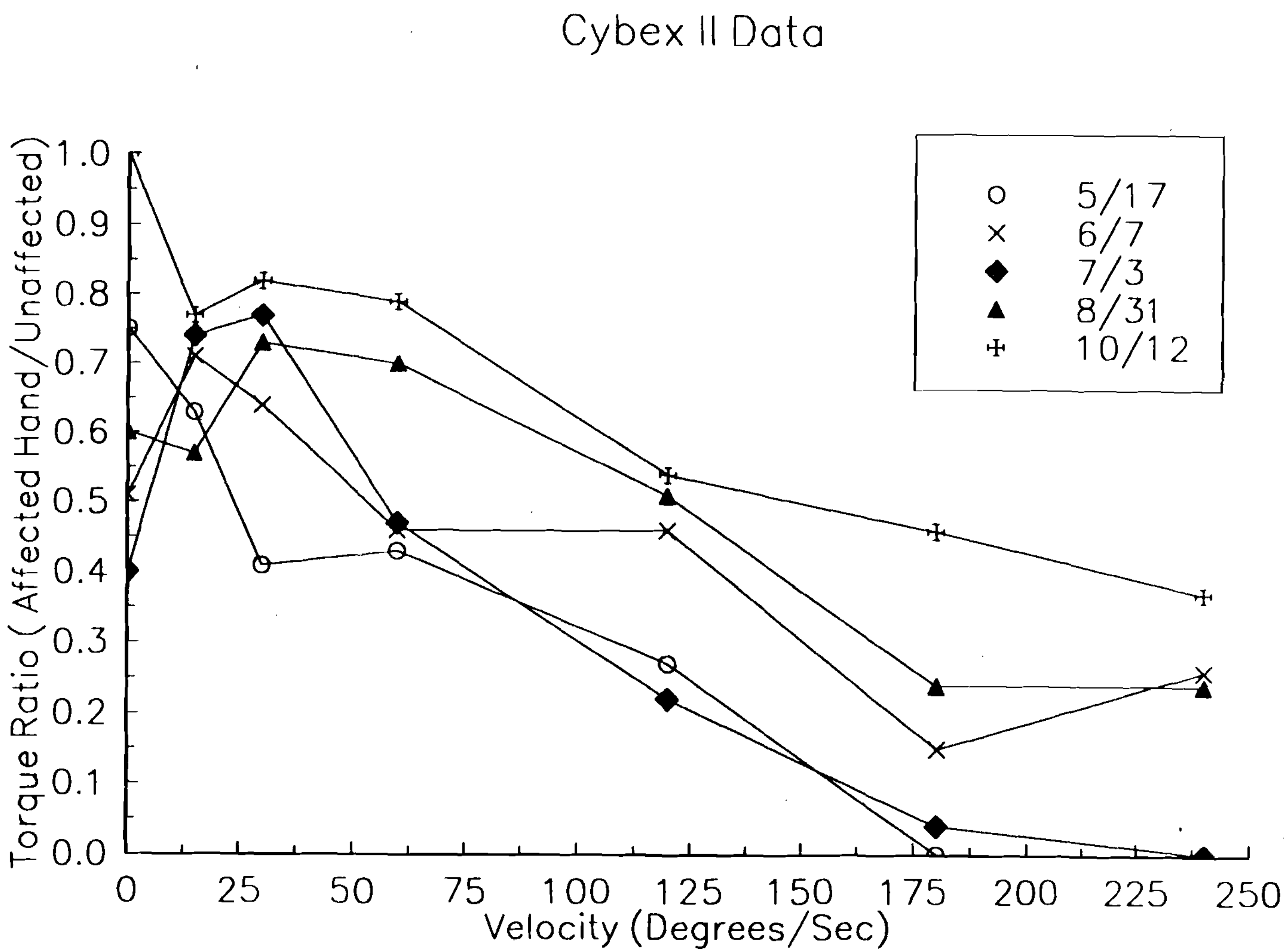


Figure 33 D.S. wrist extension torque before ending stimulation

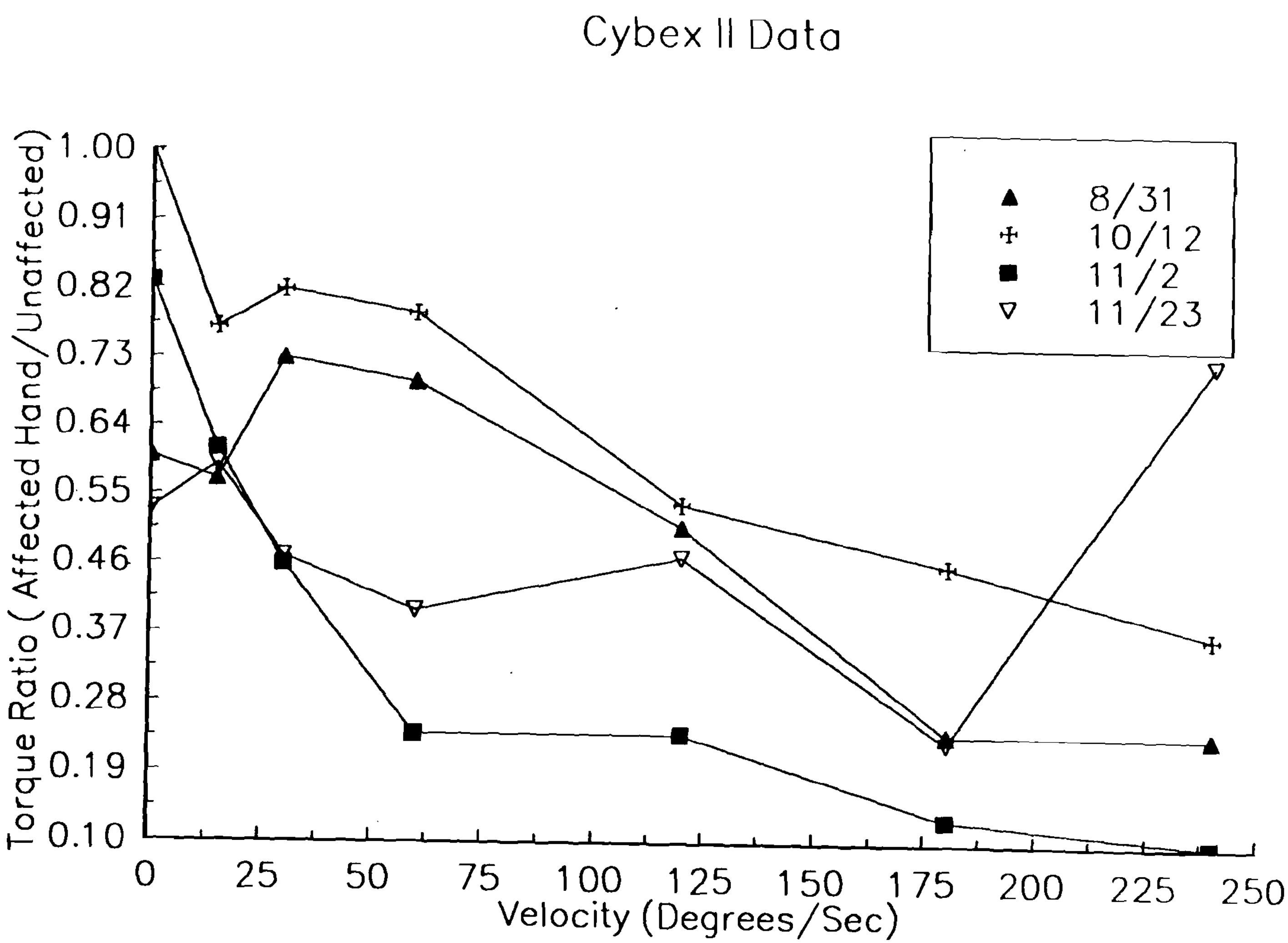


Figure 34 Comparison of wrist extension torque before and after ending stimulation

Wrist extension was the real area of interest. The six baseline measurements are plotted on day 0 in figure 35. Day 1 stands for 9/29 for this and all other plots of data generated by C.R. Mean voluntary wrist extension did increase from -40° to -20° from the first baseline testing date to the second. The next week, however, the mean wrist extension fell to -27°. The scatterplot displays a remarkably linear increase in wrist extension during the FES program until the curve exhibits a decrease in slope when it reaches 50°. The overall R^2 is 82.4%. Voluntary wrist extension increased from a baseline mean of -30° to an average of 59° by day 128.

```
MTB > plot c31 vs. c30         C.R. - Right Wrist Extension

          -
  rwexta  -                             *           2 2     *  2
          -                             2  *             2  2  *
          -                           2    *        * *
        40+                        2  * *  *
          -                        *                *
          -                   *
          -             2     2 *
          -             * 2     *
         0+       2   3   *     *
          -       *
          - 2
 Angle    -    2
          - 2  *
       -40+ *
          - *
          -
            +---------+---------+---------+---------+---------+------rwextd
            0        25        50        75       100       125
                                         Days
```

Figure 35 C.R. right wrist extension

6.3.2 Grip and Pinch Strengths

Three different hand dynamometers had to be employed during the course of the study with C.R. The instruments were shaped differently, so the only meaningful calibration method was to have C.R. perform tests with all three in one session, which he did on 2/3. Scaling factors were calculated which equated the means for the three dynamometers. The measurements made with the Lafayette and Stoelting instruments on earlier dates were adjusted by multiplying them by the scaling factors.

The six baseline measurements are plotted on day 0. The scatterplot in figure 36 shows a fairly linear increase in grip strength with the number of days in the FES program with a slope of .41 lb./day until approximately day 57. After this date little change in grip strength occurred. Direct comparisons can be made with the Lafayette dynamometer readings for the second baseline testing date and the last session of the study; right mean grip strength increased from at best 0.5 kg to 5.0 kg while average left hand grip force dipped from 40.5 kg to 38.5 kg.

The first evaluations of pinch force were obtained on day 31. The lateral pinch strength data exhibited a smaller, more gradual increase than that for grip strength. Lateral pinch strength rose from approximately 3 to 7 lb (see figure 36). The fitted regression line had a positive slope significant at p=.001. The R^2 was 53%. Left-hand lateral pinch force data also yielded a statistically positive slope. Left-hand grip and lateral pinch values were plotted in figure 37.

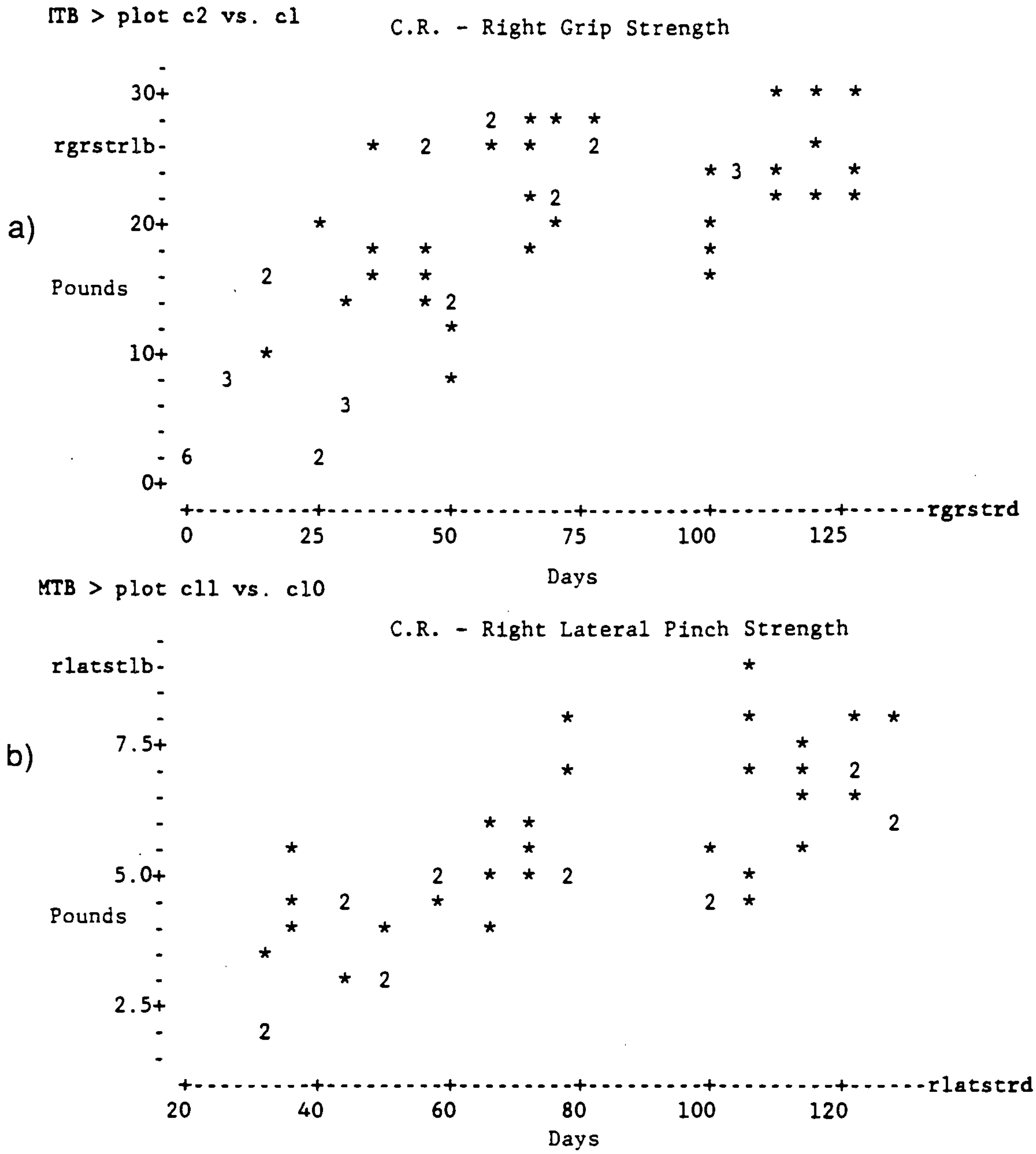


Figure 36 C.R. right-hand strength a) grip and b) lateral pinch

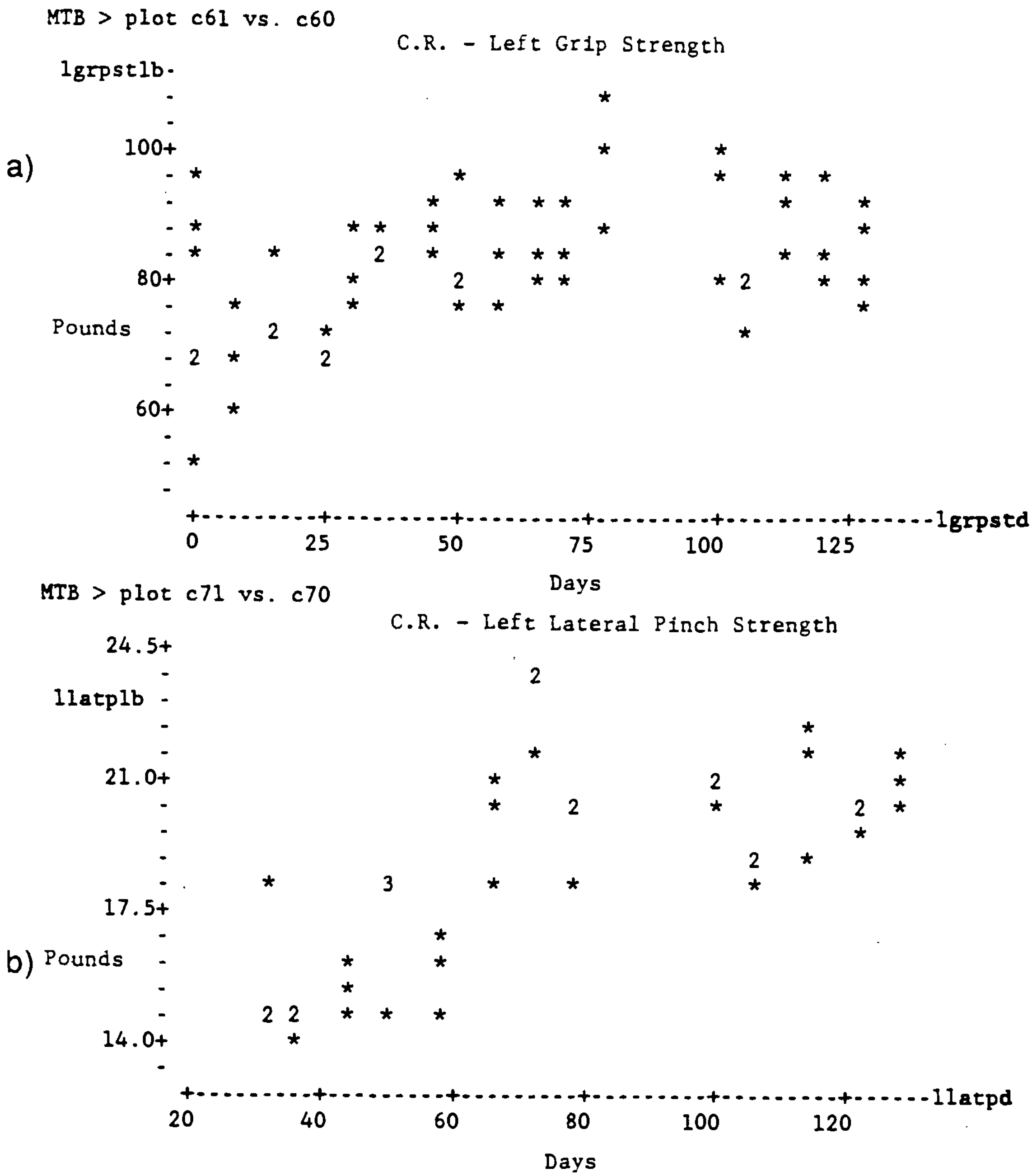


Figure 37 C.R. left-hand strength a) grip and b) lateral pinch

As can be seen in figure 38, right-hand palmer pinch strength rose sharply from means of 2.0 lb. on days 31 and 36 to the means of 7.0 lb. on days 65 and 71. After day 71 the pinch force began to decrease back toward 5.0 lb.

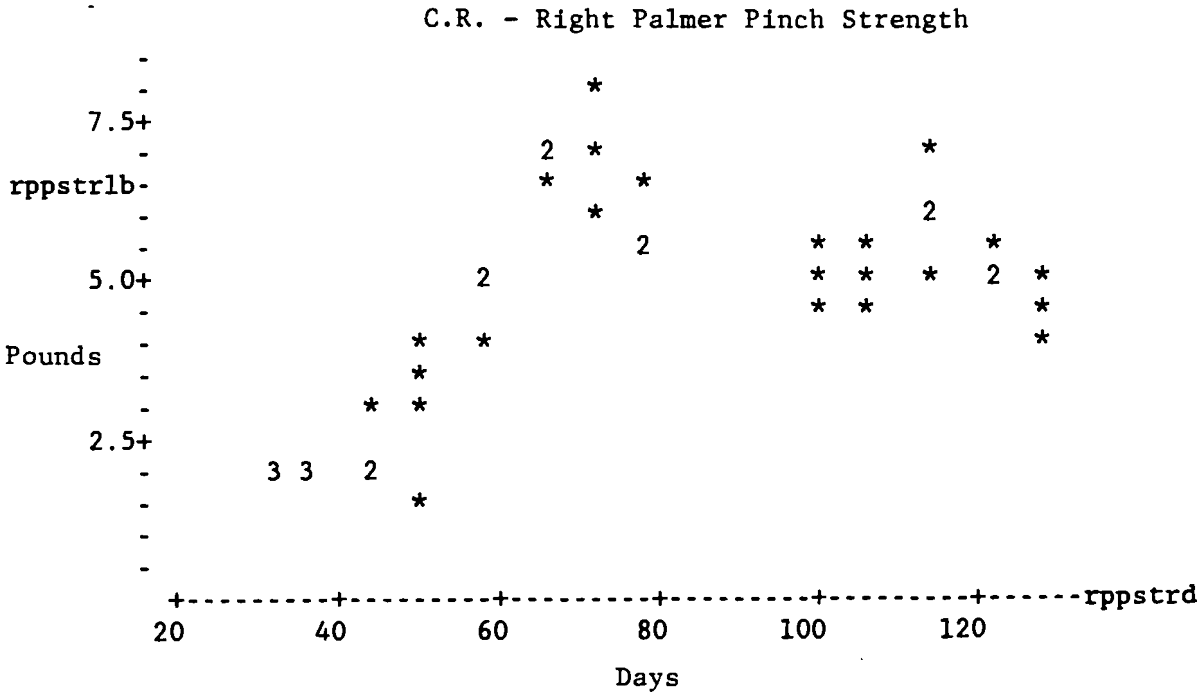


Figure 38 C.R. right-hand palmer pinch strength

6.3.3 Dexterity Tests

C.R.'s ability to control his hand during sequential movements was evaluated through the use of the tasks to pick up the pens, the balls, and the coins. C.R. had great difficulty in picking up the coins, so a time limit was set on this task. He was allowed three minutes to lift a quarter, nickel, penny, and dime, in that order, out of a box. The denominations he was able to pick up within the allotted time were documented.

In the first trials C.R. was not able to perform the tasks correctly; he had to use his first and second fingers as pincers. He did not use his thumb and first finger to pinch during the testing until day 15 for the task with the coins and day 24 for the one with the pens. Thus, these are, respectively, the first days at which data is plotted in figures 39 and 40.

Figure 39 relates which coins C.R. was able to lift out of the box for each trial. The plot quantifies the marked progress in C.R.'s control of the palmer pinching motion that he used to pick up the coins. For one of the trials on 1/12 he retrieved the dime as well as the other three coins within 7:00 and on 1/19 he did the same in 4:11.

Figure 40 documents the reduction in time needed to pick up the pens. The regression of the log transformation gave a line with a negative slope significant at $p = .001$. The R^2-value was 32%. For the left hand the negative slope for the line implied by the data was not rejected at $p = .004$; these values are graphed in figure 41 The accompanying R^2 was 17%. The mean time for the right handed performance decreased from 250.7 sec. for the first two testing dates to 175.5 sec. for the last two sessions for a 30% diminution while the left handed average times fell from 5.9 to 4.7 seconds for a 20% drop.

Testing with the 5 balls was begun on day 24. The scatterplot for the right hand, (figure 42), suggests that his performance of this task improved, got worse, and then improved again. The line of best fit for all the data has a negative slope which is statistically supported for $p = .04$, but the R^2 is only 10% because the trend was not linear. Meanwhile, regression analysis provided strong evidence for the presence of a downward trend for the amount of time to pick

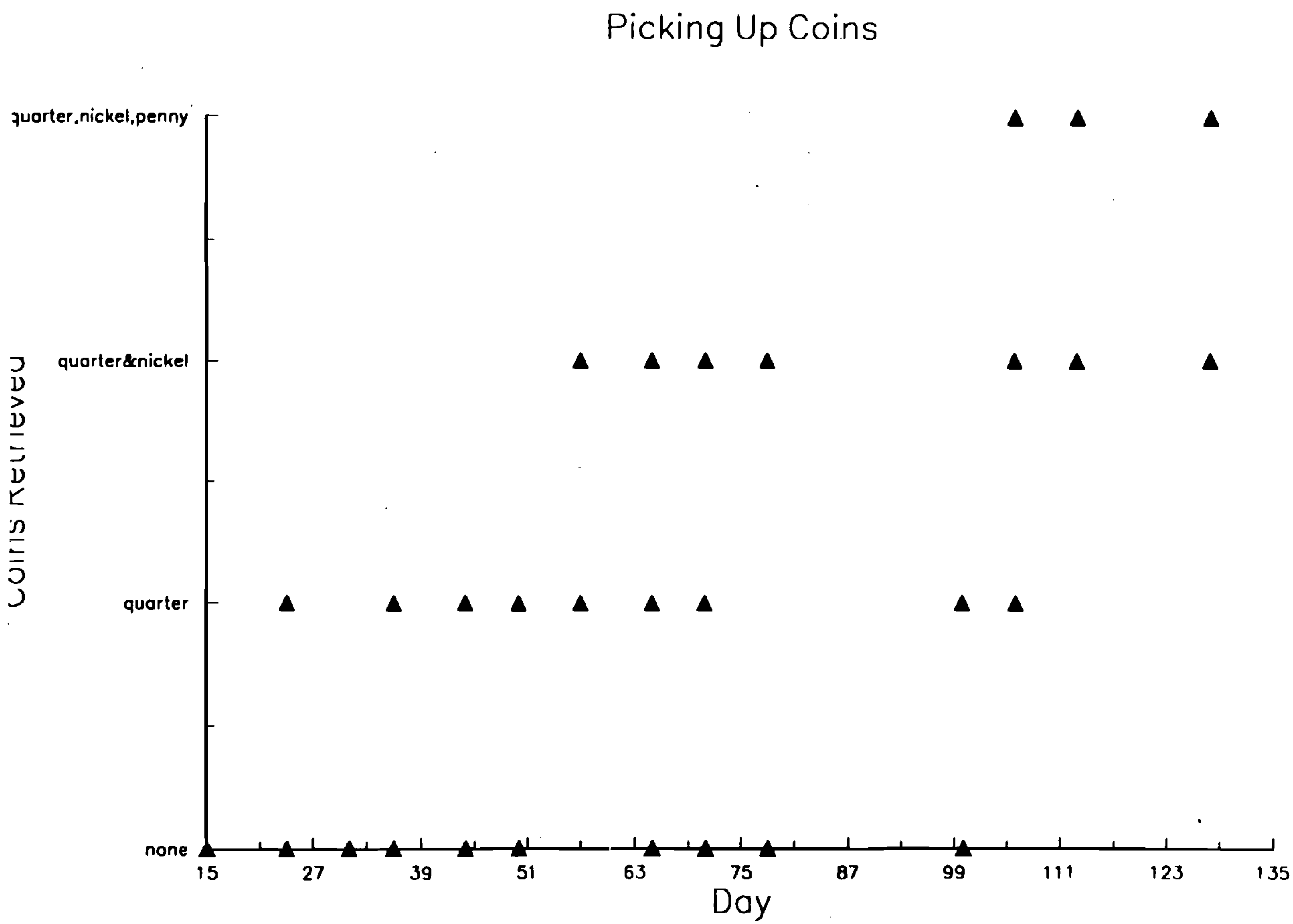


Figure 39 C.R. - right hand - picking up coins

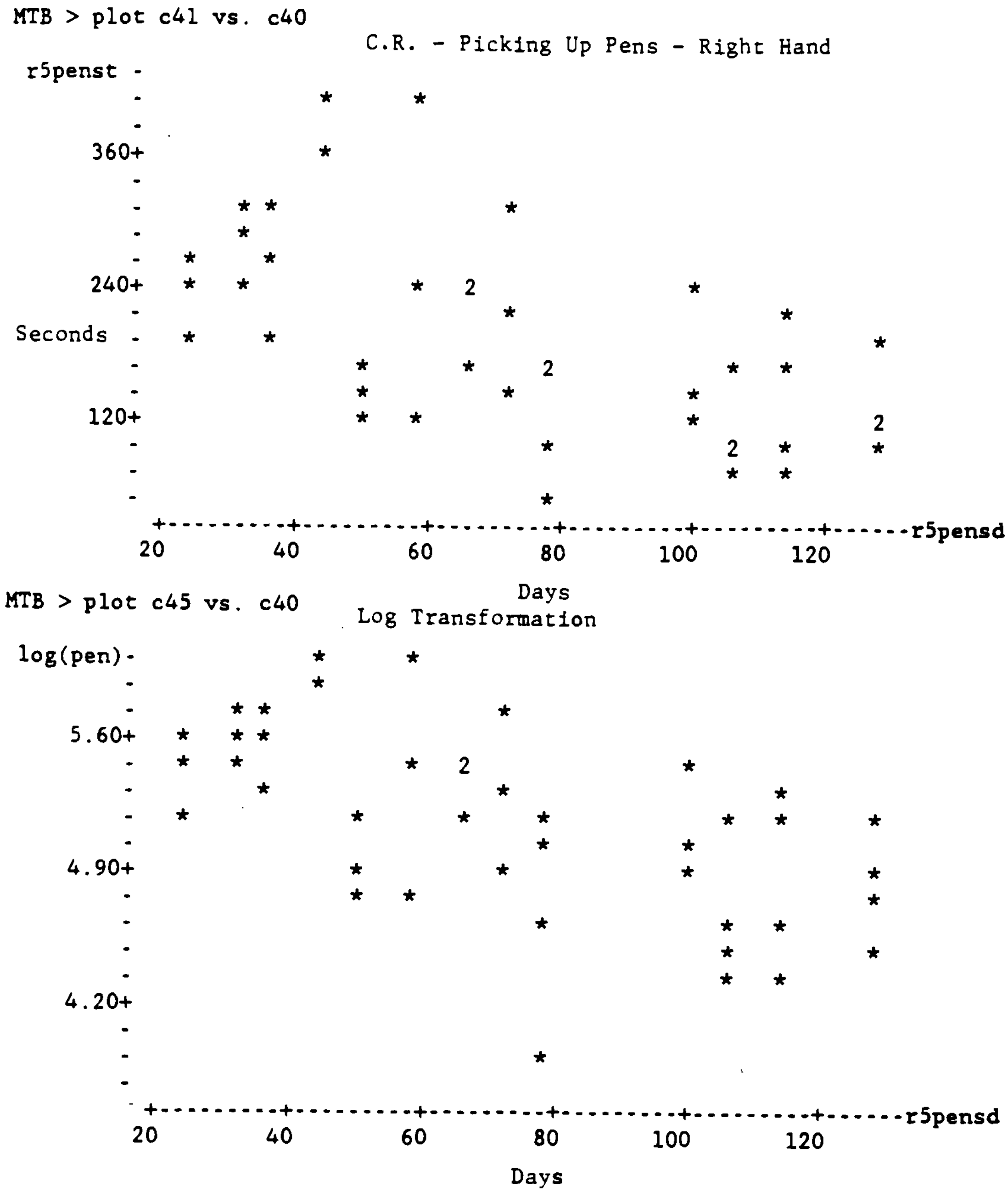
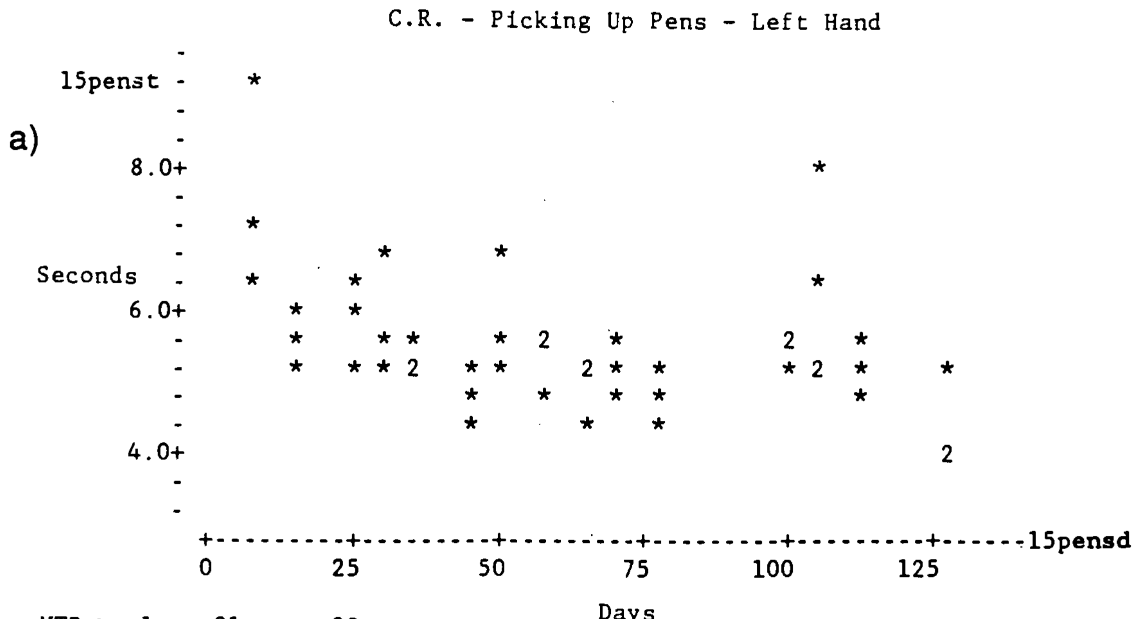


Figure 40 C.R. picking up pens with right hand

ITB > plot c81 vs. c80



MTB > plot c91 vs. c90

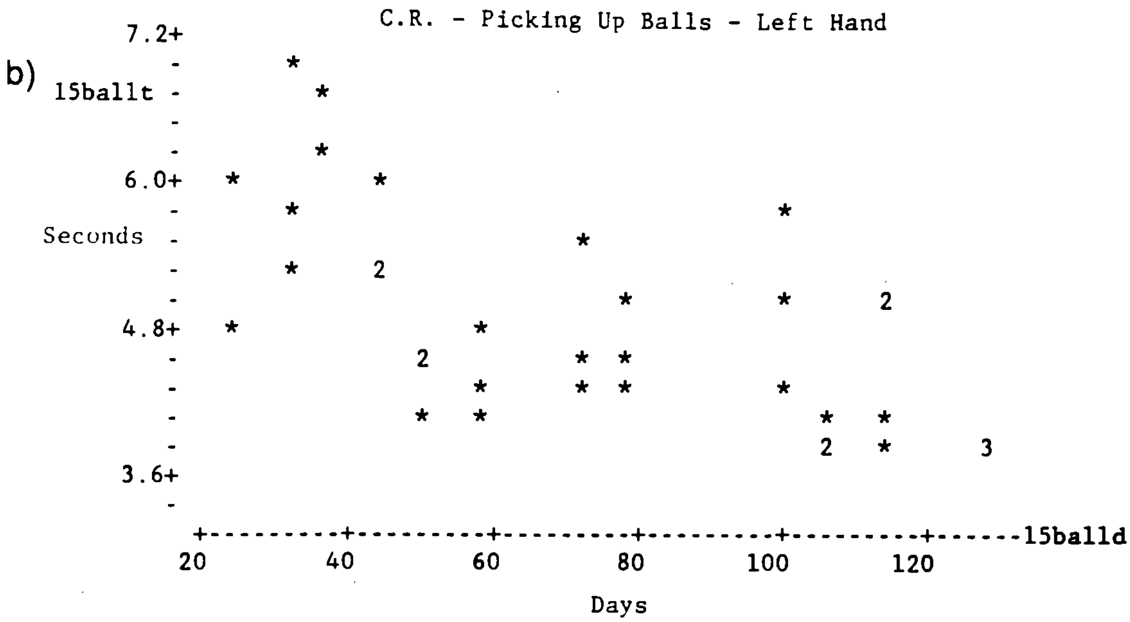


Figure 41 C.R.-left hand picking up a) pens and b) balls

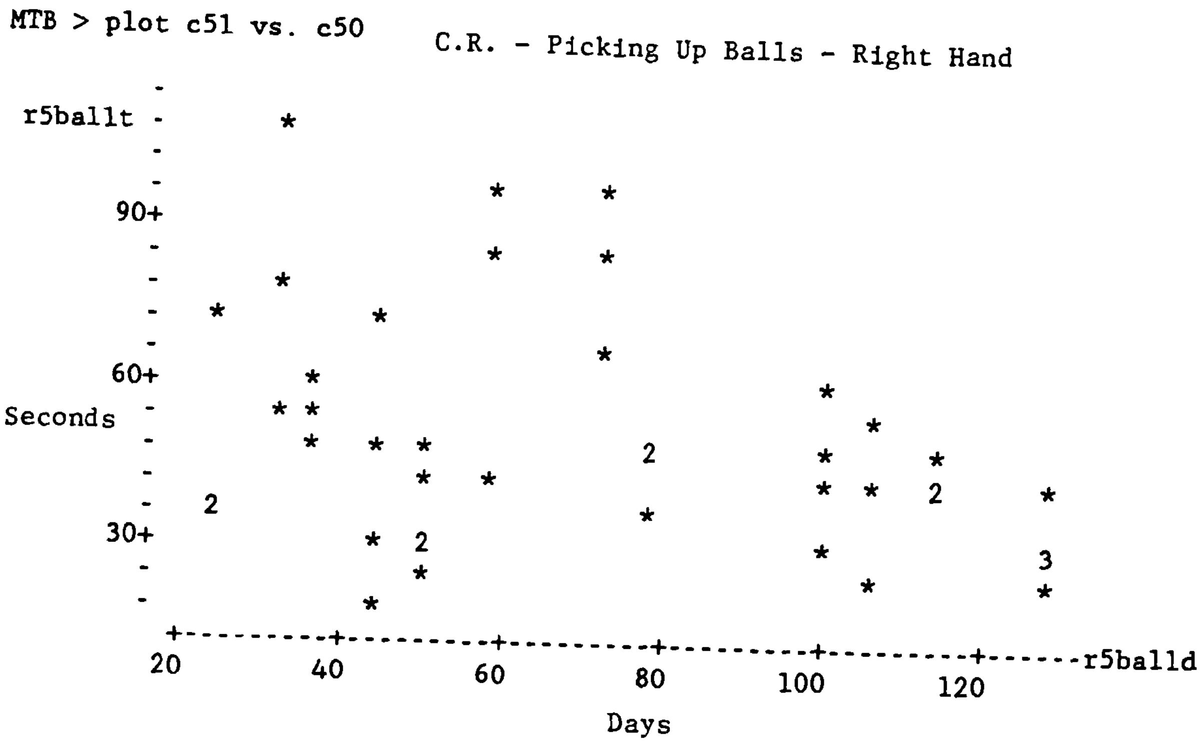


Figure 42 C.R. picking up balls with right hand

up the balls with the left hand as illustrated in figure 41. A 43% decrease occurred between the mean time, 63.7 seconds, for the right hand data taken on days 24 and 31 and the average, 36.2 sec., of that recorded on days 113 and 128. The left hand mean times decreased 23% in going from 5.8 to 4.1 sec.

6.4 M.E.

6.4.1 Range of Motion

M.E.'s thumb extension and abduction were quite good, approximately 75° and 60°, respectively, before the advent of FES therapy on 10/14. No stimulation of the muscles governing these motions was undertaken. The values for the thumb range of motion remained fairly constant throughout the period of this study.

Baseline measurements for wrist extension were gathered on three separate occasions before 10/14, day 1 for all the scatterplots concerning M.E. The average of the three angles from 9/28 was -13° and that for 10/5 was -12°. However, on the third test date, 10/13, the mean wrist extension was +15°. These measurements were taken in the late afternoon while the first two sessions had been held in the morning. There seems to have been a very strong fluctuation in the degree of spasticity with the time of day. All subsequent testing, except for one date, was done in the afternoon. During the FES program the lowest mean wrist extension, +18°, was documented on day 40, the one examination session held in the morning. Inspite of all this variability, it can be unequivocally stated that M.E. experienced an increase in voluntary wrist extension during the FES program. After the first 11 days of stimulation the mean upper limit for wrist extension jumped to 47° and then increased to 66° by the end of the study 100 days later. This is shown in figure 43.

6.4.2 Grip and Pinch Strengths

The grip force data shown in Figure 44 was assessed with two different dynamometers. M.E. used both the JAMAR and Stoelting gauges on 2/1 and the mean values recorded were equated through a scaling factor. The recordings from the one session in which the Stoelting dynamometer was employed were adjusted by this scaling factor. The Stoelting instrument was used for the baseline measurements plotted on day 0. The right-hand grip force data exhibits no statistically significant trends. However, when the

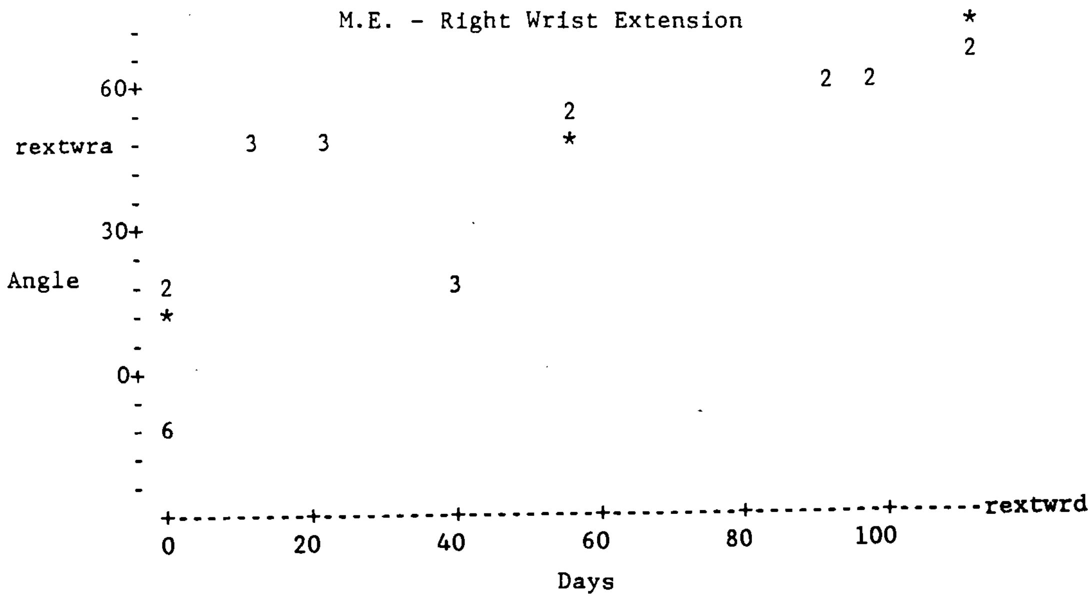


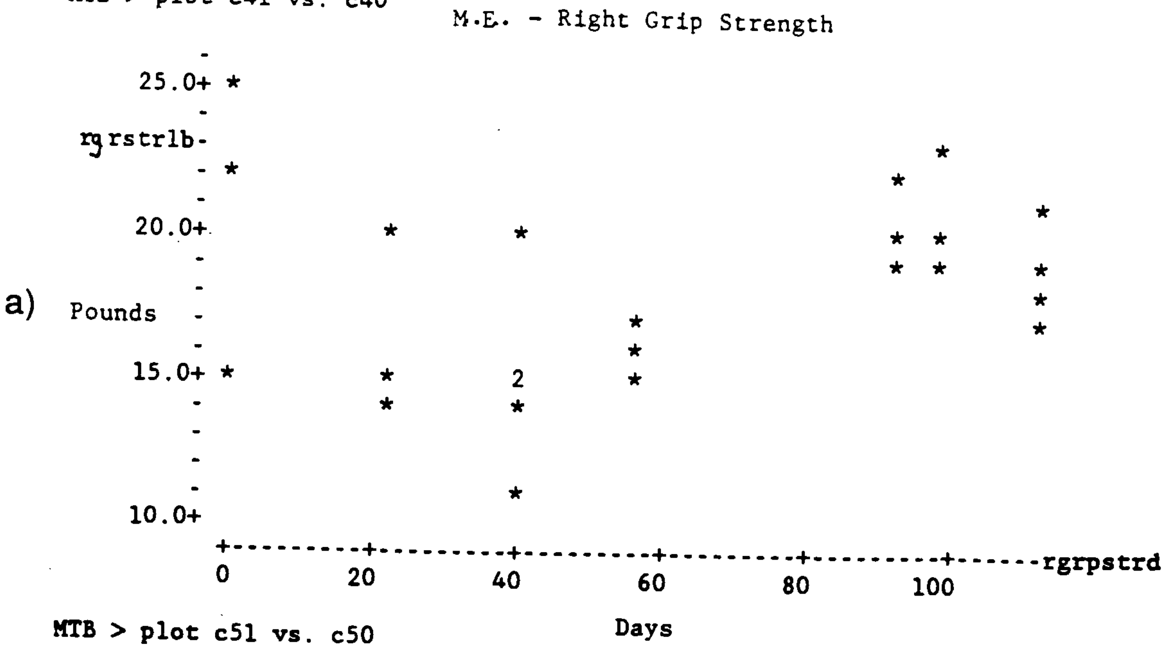
Figure 43 M.E. right wrist extension

values graded by the Stoelting instrument are removed, regression yields a slope of .056 which is not rejected at p = .003. Analysis of the data for the left grip force results in a fitted line with slope .055 significant at p=.05.

Utilization of statistics supports the visual assessment of the scatterplot for right lateral pinch strength that no patterns exist; the slope is strongly rejected at p=.05. This is illustrated in figure 45.

The linear trend of gains in right palmer pinch strength is rejected at p=.05. The mean force does increase, though from 4.1 lb. for the first two dates on which palmer pinch strength was tested to 5.4 lb for the last two sessions. The average for the left hand dipped from 13.3 lb. to 12.5 lb. Figure 46 contains the scatterplots for right and left palmer pinch.

MTB > plot c41 vs. c40



MTB > plot c51 vs. c50

MTB > plot c71 vs. c70

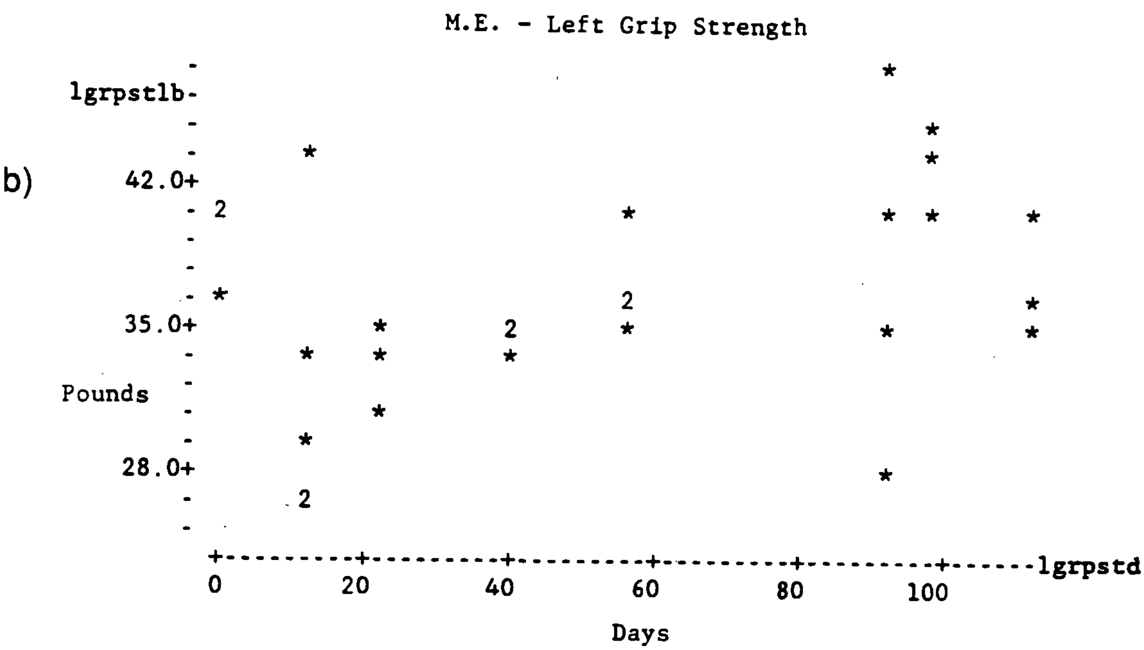


Figure 44 M.E. grip force a) right hand and b) left hand

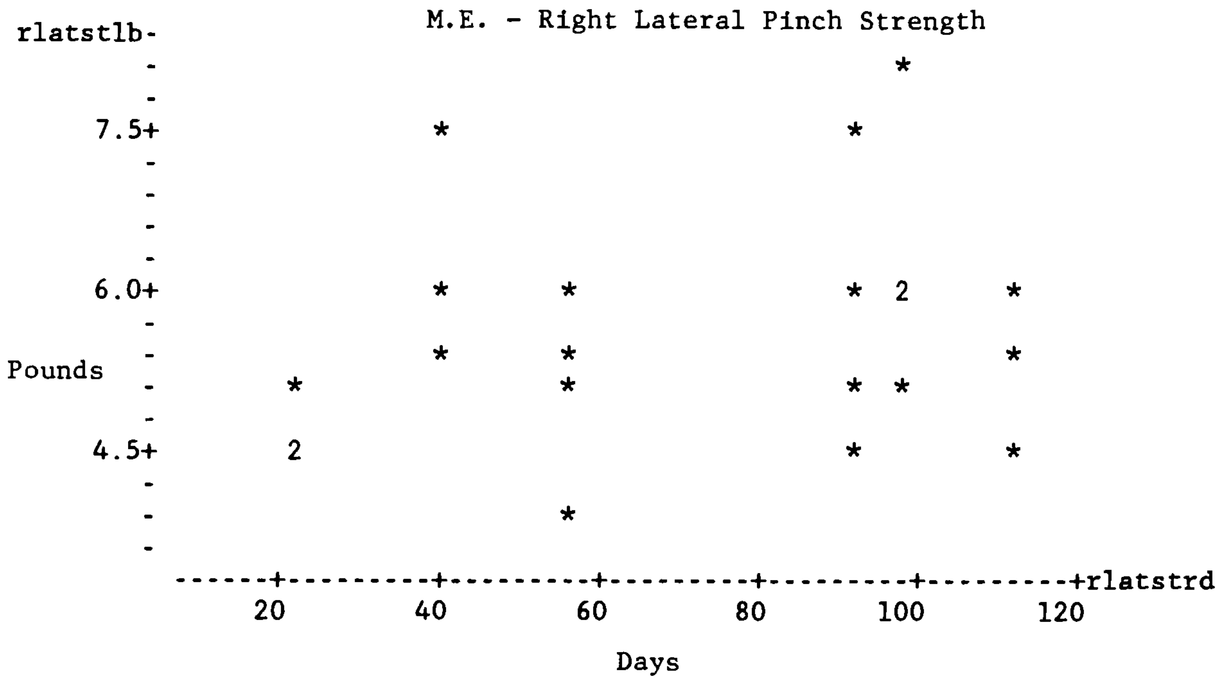


Figure 45 M.E. right-hand lateral pinch strength

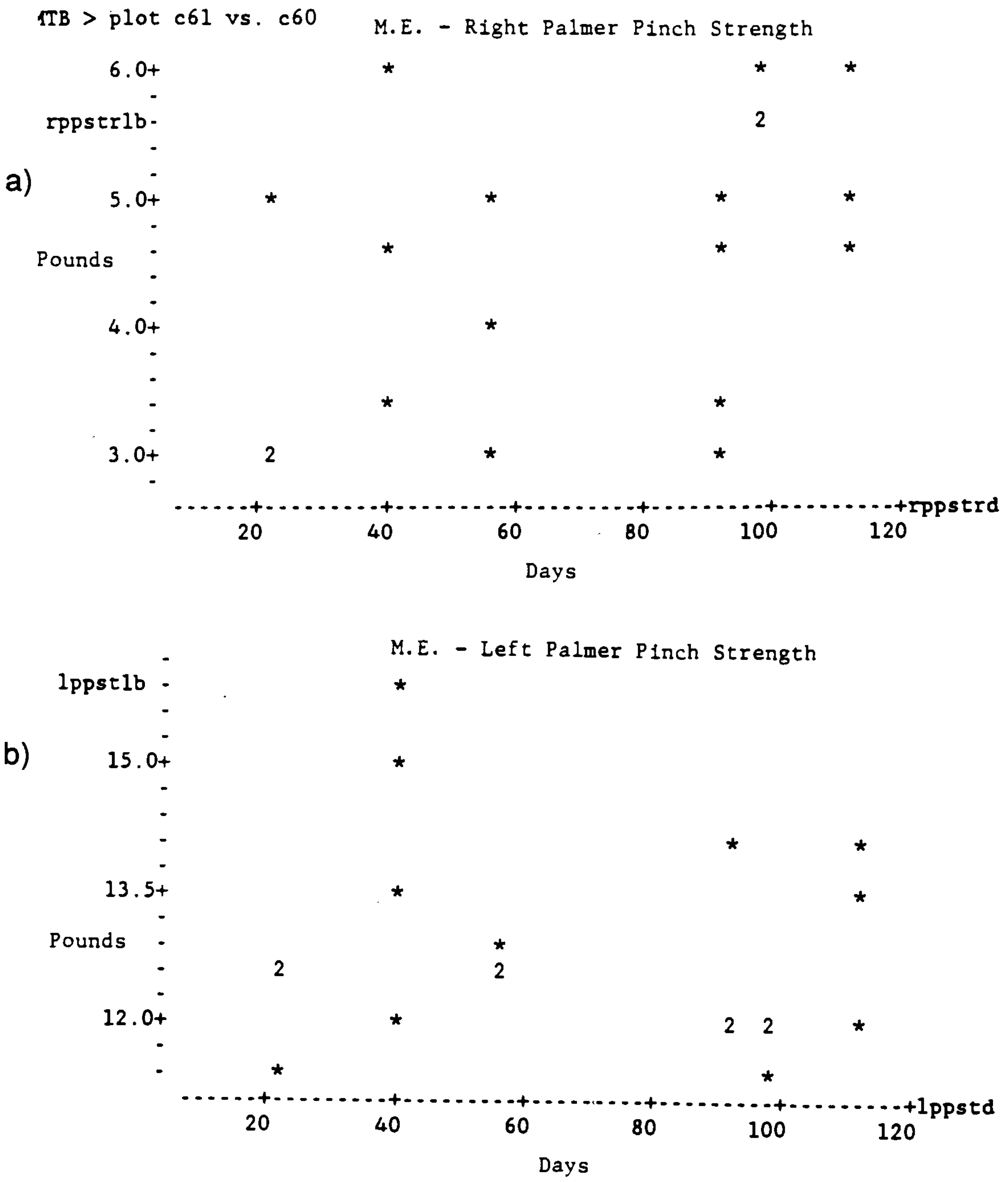


Figure 46 M.E. palmer pinch strength a) right and b) left

6.4.3 Dexterity Tests

Trials involving picking up the pens and picking up the coins were run on two dates prior to 10/14. On the second date M.E. was faster in picking up the pens but slower in picking up the coins. M.E.'s performance in regard to lifting the balls out of the box was first timed 11 days after the implementation of FES therapy.

The scatterplot detailing the time M.E. took to retrieve the coins for each trial is shown in figure 47. After initial progress, he seemingly became much worse and than improved again. His mean time in the last testing session was 91.9 seconds, which is faster than the mean of 121.5 sec. for the 10/5 baseline session but slower than the 76.1 sec. average recorded after the first 11 days of stimulation.

```
MTB > plot c21 vs. c20
                                M.E. - Picking Up Coins - Right Hand
          -
          - *
       360+                            *
          -
  rqdnpt  -          2                 *
          -
          -                    *
       240+ *
          -                    *
          -                                          *  *
 Seconds  -
          - *
       120+       *                                           *
          - *                                        2  *     *
          -          *                                  *     *
          -       2
          -
            +---------+---------+---------+---------+---------+------rqdnpd
            0        20        40        60        80       100
                                        Days
```

Figure 47 M.E. picking up coins with right hand

To analyze the data charting the progress of voluntary control of the pinching motion used in picking up the pens and the grasping motion M.E. employed to lift the balls out of the box log transformations of the times were calculated. This reduced heteroscedasticity and provided a better match between the data and a line. The original data and the log transformations are graphed in figures 48 and 50.

The negative slope of the line generated by regression analysis for the times to pick up the pens was statistically significant at a value of p=.001. The associated R^2 is 58%. Mean time to perform the task fell from 119.1 sec. for the baseline evaluations to 35.3 sec. for the final two sessions. The negative slope of the line fitted to the plot for the left hand is rejected at p=.27. The graph for this data is shown in figure 49.

Statistical analysis for the data for retrieving the balls reveals a decrease in time to completion over the course of the study to be significant at p=.004; the R^2 is 40%. The average of the four trials from the first two sessions at which testing with the balls was done is 28.8 seconds. The mean for the final two sessions is 20.9 seconds. Removal of the outlier time, which was almost twice as long as the other three times from the final session, lowers the second mean to 19.4 seconds. Definite improvement was noted in left hand performance of the same task, also. Statistics supported this at p=.004 with a corresponding R^2 of 48.7%. The mean dropped from 11.5 sec. to 8.2 sec. over the same period as described for the right hand.

```
MTB > plot c86 vs. c85
                             M.E. - Picking Up Pens - Left Hand
            -
       15.0+                     *
            -
    15penst -
            -
            -
       12.0+                                                         *
            -
    Seconds -
            - *
            -       *                     2
        9.0+ *      *    *        2                                   *
            -            *                                    *
            - *
            - *                           *                 2  2
            -                                            *           *
        6.0+
             +---------+---------+---------+---------+---------+------15pensd
             0        20        40        60        80       100
                                          Days
MTB > plot c96 vs. c95
                             M.E. - Picking Up Balls - Left Hand
    15ballt -        *
            -
            -
       14.0+
            -                 *
            -
            -                 *
            -
       10.5+                  *
            -        *                                     *
    Seconds -                                              *      *
            -                         2                           *
            -
        7.0+                                               *
            -                                           *
            -                                           *         *
            -
             ------+---------+---------+---------+---------+---------+15balld
                  20        40        60        80       100       120
                                          Days
```

Figure 48 M.E. picking up pens with right hand

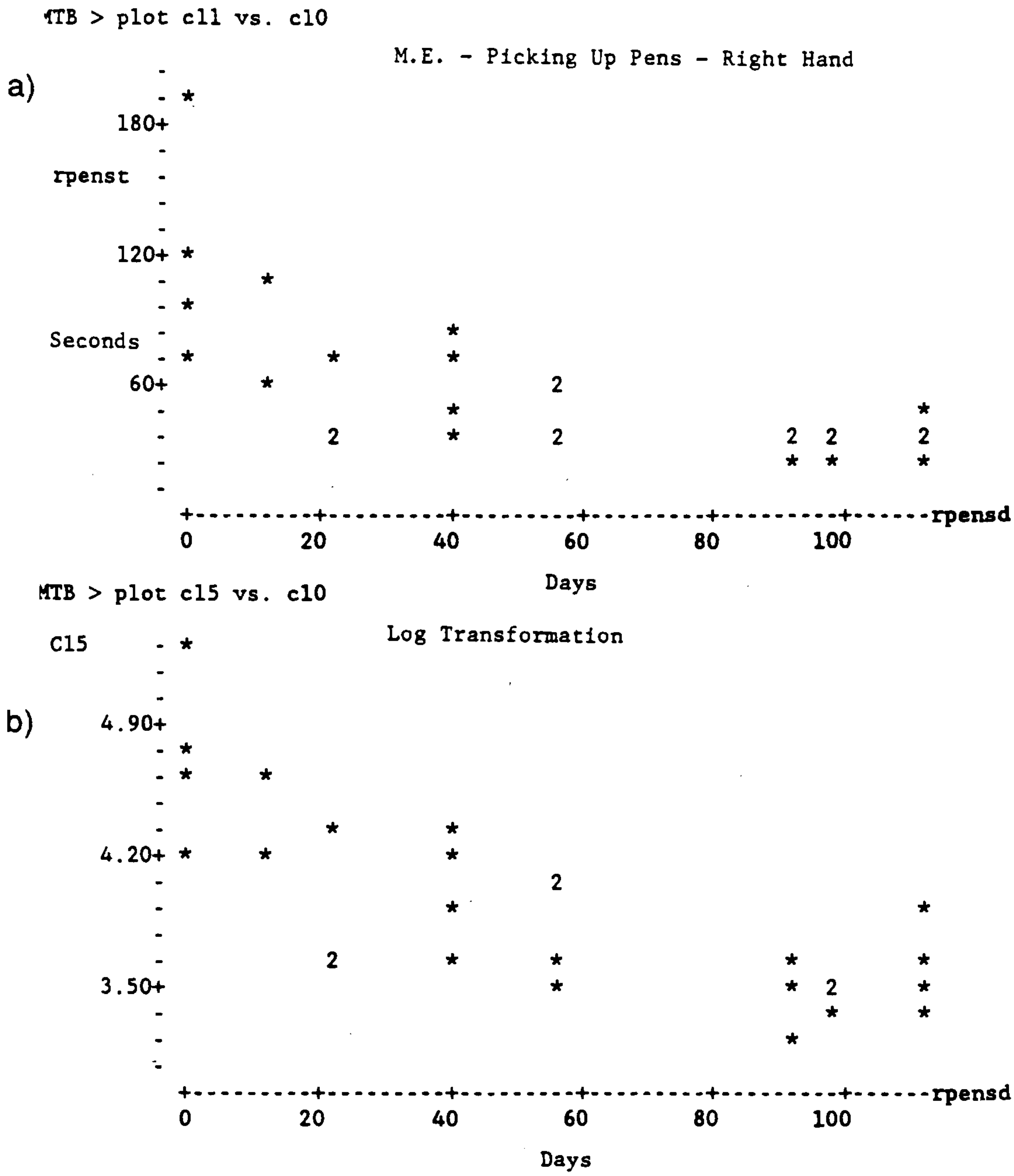


Figure 49 M.E.-left hand picking up a) pens and b) balls

```
MTB > plot c31 vs. c30
                           M.E. - Picking Up Balls - Right Hand
 r5ballst-          *
         -
         -                   *
     30.0+
         -                                                       *
         -     2    *        *                         *
         -
         -                           *                    *
     24.0+
         -                           *                 *
         -                                                *
 Seconds -                                             *  *
         -
     18.0+                           *
         -                                                       2
         -                                                       *
         -
           --------+---------+---------+---------+---------+--------r5ballsd
                  20        40        60        80       100
                                        Days
MTB > plot c35 vs. c30
                           Log Transformation
     3.50+          *
         -                   *
 log(bal)-                                                       *
         -          *                                  *
         -     2             *
     3.25+                           *
         -                                                *
         -                           *
         -                                             *  *
         -
     3.00+                                             *  *
         -
         -                           *
         -                                                       *
         -                                                       *
     2.75+                                                       *
         -
           --------+---------+---------+---------+---------+--------r5ballsd
                  20        40        60        80       100
                                        Days
```

Figure 50   M.E. picking up balls with right hand

CHAPTER VII
DATA ANALYSIS

7.1 D.S.

7.1.1 Functionality

The majority of the measurements used to gauge improvement in D.S.'s hand function indicated that definite advances were made during the course of the FES program conducted for this research.

The voluntary extension of the thumb increased to a point where the change was easily perceptible visually. Figure 51 contains pictures of peak thumb extension taken before, during, and at the end of the study. Although the data suggests that the limit of thumb extension remained constant after day 137, D.S. seemed to be able to extend his thumb further on later testing dates when performing a task, as is shown in figure 52. According to the measuring technique employed for this study the thumb extension displayed in the photo is much greater than 15°.

In contrast, the range of voluntary thumb abduction did not increase at all, even with the introduction of the golf glove. The maximum value that could be produced with stimulation alone at the end of the study was 21°, a value 8-10 degrees less than the angle he was able to form on his own. Perhaps even the golf glove failed to provide solid contact. This problem may be remedied by the use of the electrode sleeve.

The grip and pinch gauges assess primarily the force of finger and

a)

c)

b)

Figure 51 D.S. peak left thumb extension: a) 6/7 b)10/12 c) 2/1

Figure 52 D.S. extending thumb to grab pen

thumb flexion and thumb opposition, movements not addressed in this study with D.S. Increases in the grip and pinch strengths reported in the Mozelewski study, [7], were derived from the acquired ability to maintain a more stable hand posture and to place the hand in a more mechanically advantageous position; the greatest grip strength in normals is generated with the wrist in the neutral position. As these changes had transpired prior to the start of this research, it is not surprising that no further gains were made in grip or lateral pinch strength. No increases were seen in the data from the unaffected side either.

The palmer pinch motion requires much finer control of the digits than the other two actions. Thus, the attainment of the ability to place his thumb and fingers in the proper position to perform this movement demonstrates a definite gain in function for D.S. Palmer pinching is an action basic to everyday hand usage in normal individuals. A major reason why he did not show greater increase in strength was that the slipperiness of the hard plastic pinch gauge caused continual problems as his digits kept sliding off due to pressure being applied at a slightly incorrect angle. It was not permissible to alter the instrument to increase the surface friction. Still, some gain in force can be seen in figure 23.

The large reductions in time required to complete the dexterity tests again point to improvement in volitional hand control. The analyses on the data for the uninvolved hand suggest that D.S. became better at doing the tasks with his right hand through repetition. It is unknown if the learning carried over to the left side; it would indeed be very encouraging if learning of specific movements could occur in the involved side of cerebral palsy children. All the tasks involved grasping and pinching motions which, if mastered, would prove extremely beneficial in everyday life.

The tremendous progress D.S. made in picking up the coins was certainly due in part to the implementation of a new strategy; he realized that raking the coins into a pile rendered them easier to retrieve. Still, by the end of the study he was able to pick up a single dime as demonstrated in figure 53. Probably the clearest demonstration of D.S.'s advancement can be seen in figure 54 which documents the changes which took place during the FES program in D.S.'s ability to pick up a pen.

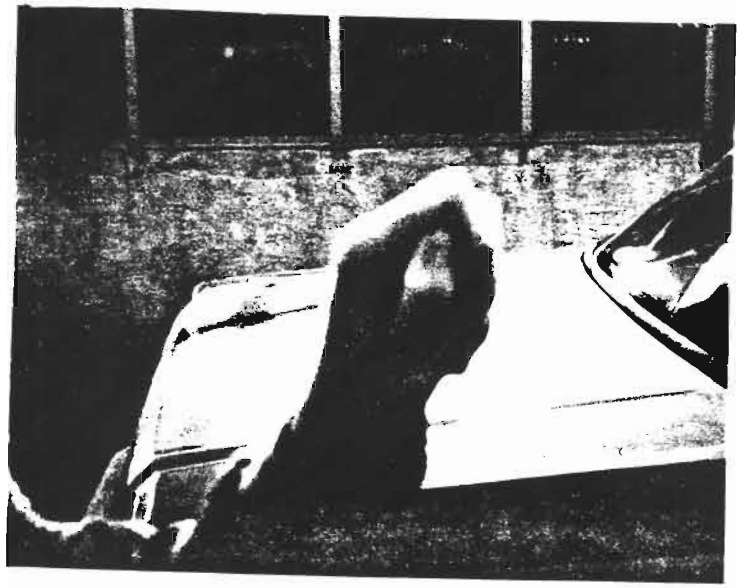


Figure 53 D.S. picking up single dime

D.S. also displayed signs of the gain in hand control outside the realm of the tests. He began to hold objects with his left hand and to use both hands in eating. He started dribbling a basketball with his left hand and reached the point where he could bounce it 20-30 times in a row. When washing dishes he can now balance pans filled entirely with water with his left hand while he scrubs them with the other hand. Near the end of this study he voluntarily crushed a soda can with his left hand for the first time. The most striking example of improved function took place one day when D.S. was accidentally pushed toward a wall. For the first time ever he put out his left hand in a reflex action to catch himself. On prior occasions he would have just crashed into the wall. This time he put his affected hand in the correct position and righted himself. Unfortunately, he did sprain his wrist, but it healed within a few days without any loss in performance.

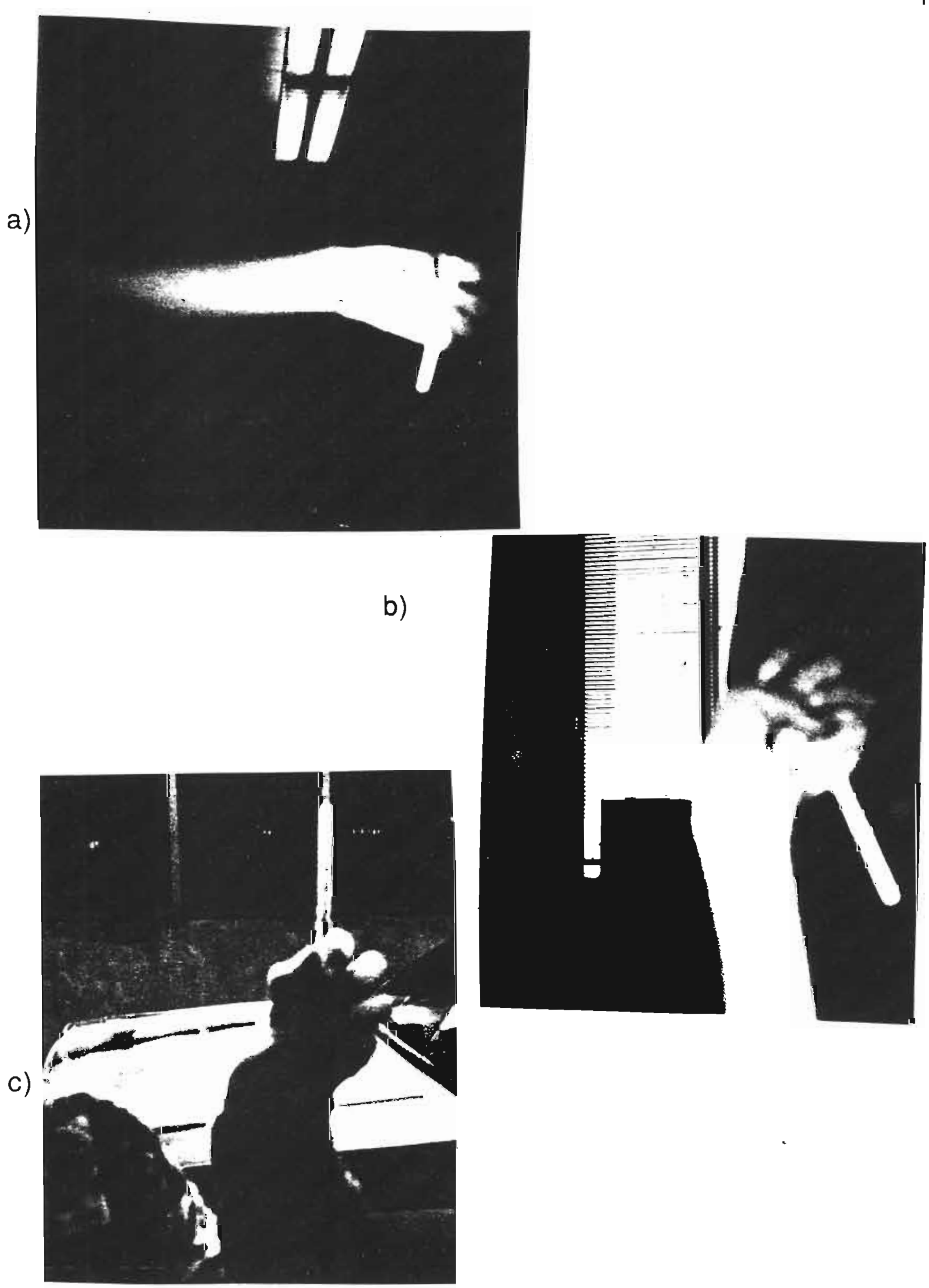


Figure 54 D.S. picking up a pen: a) 6/7 b) 10/12 c) 2/11

7.1.2 Continued Progress

This research also used data recorded from D.S. over a prolonged period of time to examine if an upper limit on improvement existed. Measurement of D.S.'s voluntary wrist extension was continued from the study preceding this one [7]. The range of wrist extension in the left arm continued to increase from the 59° angle recorded at the end of that study until reaching the maximal mechanical stretch of the ligaments and tendons. At this point voluntary extension was greater in the involved wrist than in the uninvolved one.

Until wrist extensor stimulation was ended the Cybex data also illustrated D.S.'s continued improvement in terms of the force of wrist extensor contractions he could produce at the higher velocities. A drop did occur between 6/7 and 7/3 but this corresponds to the period in which he had stopped using the 3.5 lb. weight when exercising his wrist in order to begin to work on thumb extension but had not yet started to use the Theraband®. The changes may also have been due in part to variations in the calibration of the Cybex.

By 10/12, the date marking the end of 37 weeks of wrist extensor FES, left extensor torque had risen to a value .8 that of right extensor torque for the slower speeds of extending the wrist at 15°/sec., 30°/sec., and 60°/sec. The torque generated by the left arm was approximately half of that produced by the right side for the three highest speeds. As mentioned previously, spasticity is velocity dependent. Thus, one expects to see the ratio to decrease at the higher speeds. The Mozelewski study reported that D.S. was originally unable to create any force at 120°/sec., 180°/sec., or 240°/sec. [7]. Nine months after the start of the FES program marked gains over the previous levels were still being made at the higher velocities.

7.1.3 Removal of FES

On 10/13, day 148 of this study with D.S., electrical excitation of the extensor carpi ulnaris was discontinued as described in section 5.2.1. Trends in the measurements taken before and after this date were compared.

The angles quantifying the range of wrist extension during the period without stimulation remained grouped around the value of 90° observed on 10/12. No breaks in the patterns for grip and lateral pinch strengths after 10/12 are discernible. Palmer pinch strength actually increased after 10/12, but this change was undoubtedly due to progress in the control of the thumb. Performance in all the dexterity tests continued to get better after 10/12. Thus, function definitely did not worsen; it is unknown if ending the stimulation of the wrist slowed the rate of improvement.

The only method of evaluating what was happening to the wrist extensor muscles themselves was to test D.S. with the Cybex. As can be observed in figure 32 a dramatic decrease in left wrist extensor torque relative to that produced by the right arm seemed to occur between 10/12 and 11/2. Yet, ratios from the 11/23 session had risen significantly back toward the values recorded on 10/12. The ratio at 240°/sec. even surpasses that of 10/12. This last point is questionable as one of the torque values at 240°/sec. was the highest value recorded that day for any speed for the left hand. This appears to violate the force-velocity relationship for muscle fibers in which force decreases with velocity. Perhaps D.S., realizing that it was the last set of contractions for the day became highly motivated, or, possibly, unbeknownst to the observers, he used his body to help raise his wrist.

The large decreases between the ratios for 10/12 and 11/2 may have resulted from D.S. failing to work the extensor muscle to fatigue without the impetus provided by the stimulation. A reminder issued after 11/2 to really work the muscle may have led to the improvement seen on 11/23. Drawing conclusions about the effects on the wrist extensor muscles of discontinuing stimulation with any degree of confidence is impossible given the data available. Unfortunately, D.S. sprained his wrist before further Cybex testing could be conducted.

7.2 C.R.

C.R. made substantial gains in the voluntary manipulation of his involved hand. Much of the progress was marked enough that it was easily seen as well as quantified.

Figure 55 captures the increases experienced in the peak wrist extension during the FES program. Accompanying the better wrist extension was improvement in the ability to flex the fingers. It should be noted that the earliest photo in figure 55 shows the fingers extended while in the subsequent pictures of C.R. trying to extend his wrist the fingers are flexed into a fist. The actual gain in the range of wrist extension was even greater than the 79° difference between the highest baseline mean and the highest mean value quantified after the introduction of FES. The testing appeared to generate anxiety in C.R. which worsened his dystonia. Greater wrist extension was observed in C.R. outside of the testing sessions

a)

b)

c)

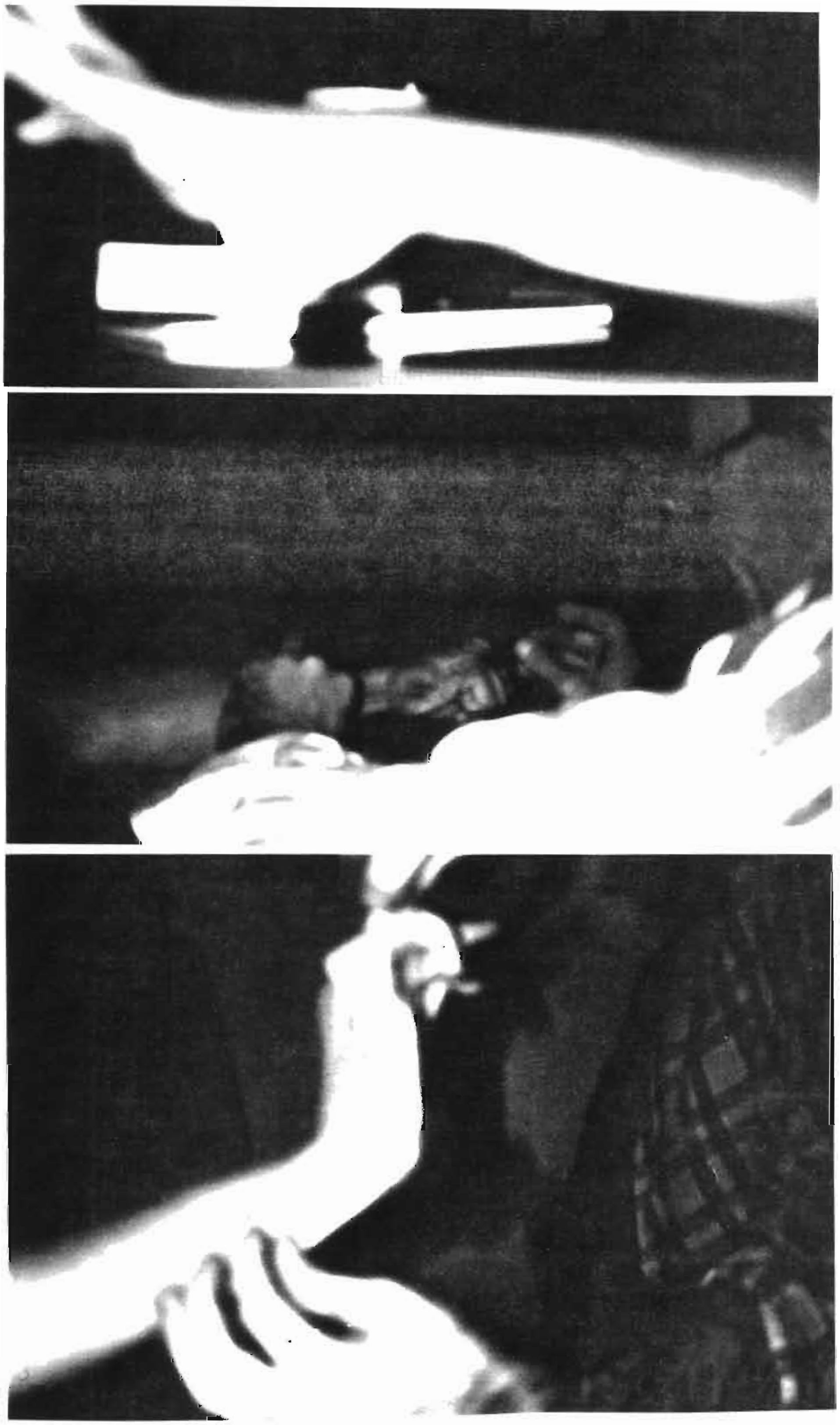


Figure 55 C.R. voluntary right wrist extension: a)10/6 b)12/7 c)1/27

than was ever measured.

C.R.'s attainment of the ability to voluntarily curl his fingers along with the better wrist extension translated into a 1000% increase in grip strength between a testing date before the start of the FES program and the final examination session. The better functional control of his hand allowed C.R. to increase the force of his lateral pinch strength as well. Lack of availability of a pinch gauge precluded obtaining measurements before the FES program was instituted. Greater than a 100% increase in lateral pinch strength was documented between day 31 and the end of the study on day 128.

The fluctuations in peak palmer pinch force seem to correlate well with the stimulation regimen of the abductor pollicis brevis. The strength data increased slightly after the excitation of the thumb extensors was begun on day 44 of the program. C.R. then made substantial gains during the first three weeks after the introduction of electrical excitation of the thumb abductor on day 51. A change in the FES therapy was implemented on day 72; the amplitude used to produce the thumb abduction was reduced such that less thumb abduction was generated. Hand function as measured by the performance of the three dexterity tests had worsened during the period delineated by days 51 and 72 and control of the thumb and fingers was visually poorer as well. Perhaps spillover excitation had had been working the thumb flexor, an already hypertonic muscle. In the weeks after the reduction of the charge supplied to the abductor palmer pinch strength decreased.

The real problem with C.R.'s palmer pinching motion lay in his inability to rotate his first and second fingers to directly oppose his thumb. The fingers pushed straight down while the thumb pushed at a slight angle and, therefore, slid off the slick pinch gauge.

The most remarkable progress in C.R.'s hand function lay in the switch in his pinching motion; he changed from using the first and second fingers as pincers to pinching with the first and second fingers in opposition to the thumb. Pictures documenting the switch are found in figure 56.

Improvement in the performance of the dexterity evaluations was seemingly interrupted by the period between days 51 and 72 described earlier. It is possible that as variable as his voluntary control could be from minute to minute because of the dystonia and spasticity, he just experienced a bad three-week stretch. Yet, it is certainly suggestive that the week after the amplitude of the thumb abduction was reduced the dexterity times decreased and remained better thereafter. The overall reductions in time needed to complete the tasks was greater both in absolute value and percentage for the right hand than for the left hand.

C.R.'s progress in picking up the coins coincides with the incorporation of stimulation of the finger flexors into the therapy starting on day 79. Where he was originally unable to get any of the coins, by the end of the program he was able to extract them all. Even though he never lifted all the coins out of the box within the allotted time, his motion became so much better and he was sometimes so close to getting the coins that he actually wanted to keep going past the three-minute mark. In a few trials he did indeed eventually get all of them.

At the end of the study C.R. was still hampered by the slow, writhing movements inherent to dystonia. Sudden onsets of

a)

b)

Figure 56 C.R. right-hand palmer pinching motion a)10/13 b) 2/16

a)

b)

Figure 57 C.R. picking up a pen with the right hand a)10/6 b)3/1

spasticity also occasionally prevented voluntary motion. Anxiety and frustration heightened these effects, thereby leaving no option but to try to relax and wait until the problems dissipated, usually within several seconds. Inspite of this, C.R. has noticed a difference in his control of his hand. For example, he has started to use his right hand to pick up pencils when he drops them at school and has gained the ability that, when he spontaneously wants to clap his hands, he does so in a normal manner, with his right wrist extended. Figure 57 illustrates the amelioration in C.R.'s hand manipulation in picking up a pen.

7.3 M.E.

M.E.'s spasticity was much milder than that exhibited by the other two subjects prior to beginning to employ FES on 10/14. His lateral pinch and grasping motions were quite good.

One of the primary goals with M.E. was to increase his volitional range of wrist extension. His typical wrist extension was somewhere between -12° and 15° before 10/13 and up around 60° after the study. The pictures in figure 58 show the difference.

Peak grip force is generated in normals with the wrist at 0° extension. With his baseline wrist extension falling somewhere around this value and his possession of a fairly good grasping motion, it is not surprising that his grip strength showed little improvement. As he could already perform a fairly good lateral pinch before beginning FES one would not expect much improvement in lateral pinch strength and none was seen. With his good thumb range of motion it is not surprising that little change was observed in palmer pinch strength either.

a)

b)

Figure 58 M.E. right wrist extension: a) 10/6 b) 2/1

The time M.E. needed to pick up the coins decreased, increased, and then decreased again over the course of the treatment. M.E. used a grasping rather than a pinching motion to pick up the coins. Thus, his hand screened the desired coin from his vision when he went to lift it out of the box. As his sense of touch in his hand was very poor, he could not make any fine adjustments based on the sensing of changes in coin position as he pulled the coin into his palm. He had to grasp, lift his hand, and then open it to see if he had retrieved any coins. This required persistence and sometimes he became frustrated and his mind wandered. The motion did appear to get better, though. Where originally M.E. seemed to have to thrust his hand into the bottom of the box, by the end of the study he had sufficient control of wrist extension to place his hand in the desired location and position.

This change resulted in the reduction in the time necessary to pick up the balls. He became more adept at holding his hand above the bottom of the box, thereby leaving his fingers free to grab.

The decrease in time needed to lift the pens out of the box and put them into a cup stemmed largely from an unexpected improvement in the range of supination. M.E.'s voluntary supination was not measured, but its increase during the program became so obvious that it was definitely noted. The better supination greatly facilitated placing the pens in the cup for M.E. since the length of the pens was greater than the diameter of the cup.

His performance of all three dexterity tests became much smoother with his right hand as the study progressed. His grasp-and-release motion became quite fluid by the end of the study (see figure 59.) However, M.E.'s parents were unaware of any tasks in everyday life for which M.E. used his right hand at the end of the study that he had not been doing before beginning the FES program. A primary reason for this lack of use of the supposedly increased hand control was that M.E. had become very adept at operating with only one hand. Well established patterns would have to be broken before he would make more frequent use of his right hand.

Figure 59 M.E. releasing a pen

CHAPTER VIII
CONTROLLER

8.1 Problem Statement

The three subjects made advances in voluntary control of the extremity affected by CP. Based on observations made in this research and by others [4,7], the possibility that the visual and proprioceptive feedback resulting from the repetition of certain movements, such as thumb extension, played a role in the progress seems likely.

Entire grasp-and-release or pinch-and-release sequences were not produced. Rather, parts of the movements were generated independently. For example, wrist and thumb extension would be repeated for thirty minutes and then thumb abduction and finger flexion created for another twenty minutes. Coordination of the two pairs of motions is quite awkward given the the stimulators commonly used in clinics.

The Respond II® is designed to have its parameters set once and then left alone. All the variable settings are controlled by manually turning dials. The on and off times for both channels of one stimulator are forced to be identical by the manufacturer's design. The only possible sequencing is afforded by a reciprocal option which causes alternation between the state in which channel one is on and channel two off and the condition of channel one being off and two on. Other commercial stimulators available in the U.S. are very similar. To incorporate more than two channels of stimulation one must delay turning on a second stimulator for the desired lag time and have all of the settings for the on and off times at the necessary values. This is clearly awkward and very inflexible.

Past researchers have attempted to overcome these limitations by using external means to drive the stimulators. The Respond II® is equipped to allow for an external connection which controls when the stimulation is on. The stimulator outputs its signal when an external circuit connected to the accessory jack of the stimulator is closed and stays dormant as long as the circuit is open. When a connector is plugged into the accessory jack the stimulator sends out a small current through the jack; it determines the state of the external circuit by the amount of return current. The heel switches described in chapter two have been used to control the state of the external circuit; pressure from the heel closes the circuit thereby turning on the stimulator. At OSU mechanical toggle and pushbutton switches regulated by the subjects have been employed to drive up to four channels of stimulation used in sequencing gait movements in cerebral palsy and paraplegic subjects [4,8].

The idea behind this research was to coordinate the on and off times for a number of stimulators with electronic switches. These switches would enable very fast, precise, and flexible sequencing. They could also be regulated by a programmed microprocessor.

8.2 Specifications

The electronic switches were to be incorporated into a controller which permitted user interaction. The controller had to be designed such that it could be easily operated by potential subjects at their homes. Thus, it was decided to make the device compatible with commercial stimulators approved for home operation. The controller was designed specifically for the Respond II®, but it should work for any stimulator which has the accessory jack intended for use with a heel switch. This is a common feature in stimulators. In fact, some stimulators, like one produced by Medical Designs, Inc., have separate accessory jacks for each channel. The device needed to function without the support of any other equipment aside from the stimulators. It had to be light and easily portable.

As with all devices intended for human interaction, safety was a primary concern. It was decided that the controller should not directly tamper with the output signal of the FDA-approved stimulators. All regulation was to be exercised through external circuits attached to the accessory jacks. These jacks are put in the stimulators for just such a purpose, and, therefore, none of the stimulators' safety features would be bypassed or overridden. Amplitude, pulse width, and pulse frequency cannot be increased by any sort of manipulation available through the accessory jack. Even if the electronic switches in the external circuits were to somehow short, the worst scenario would have the stimulators turned on at settings normally used by the subject. The stimulators could easily be turned off manually.

The key attribute of the controller was to be its flexibility. The user would program the desired timing of up to four different stimulators or channels of excitation, depending on the type of stimulators used. The programmed sequence would be repeated until the user decided to stop it. Completely orthogonal regulation of each of the four switches would maximize flexibility. Table 12 summarizes the desired controller operation.

Two other specifications for the device were that it be as inexpensive as possible and be built with readily available parts.

Table 12 - Desired controller performance

1. Control n = 1,2,3, or 4 stimulators
2. Drive each independently of the others
3. Turn each of the n stimulators on and off at prescribed times
4. Enable the user to program in seconds exactly when each stimulator should be turned on or off

8.3 Hardware

The first step in the design process was to determine if the impedance provided by electronic switches when they are in the "open" state was sufficient to appear as an open circuit to the stimulator. It was experimentally determined that resistances in the circuit wired to the accessory jack above a threshold of approximately 125 kΩ turned off the stimulator. This is well below the impedance provided by JFET switches. The stimulator puts a 50 μA current out the accessory jack while the switch when in the open state allows a leakage current of less than 1nA. The LF13331 JFET analog switch was chosen for this project. It can operate with a 5-volt power supply and can be driven by TTL logic. Four switches exist on each chip.

Testing was performed to ascertain how quickly the stimulator could respond to the control signal coming from the switches. Experimentation led to the discovery that the pulse width of the stimulator output signal could be shortened from its normal 300μsec. duration. For example, keeping the analog switch closed for 60 μsec. translated into a 100 μsec. stimulation pulse width while keeping the switch closed for 1.4 msec. produced a rectangular pulse of a 200μsec. duration. As described in section 5.1.4 the pulse duration plays a part in determining the voltage seen at the electrode on the skin. Thus, it is possible to indirectly vary the amplitude of the voltage applied to the skin by altering the amount of time for which the switches are closed. Amplitude modulation was beyond the scope of this project, however. In the controller the analog switches were always closed for at least a second, so the stimulation pulse width was always 300 μsec., discounting the rise and fall periods.

The digital electronics to regulate the analog switches was then designed and built. A block diagram is shown in figure 60. The MC6809 microprocessor was chosen to serve as the core of the device. The speed and computing power of this chip is more than sufficient for this project. This CPU also is quite inexpensive (see parts list in Appendix C.) The primary reasons for selecting the MC6809 were prior experience in working with it and the availability of the HP64000 Development System which provided excellent emulation and debugging facilities. The microprocessor timing was regulated with a 3.59 MHz crystal. All input and output lines to and from the CPU were buffered.

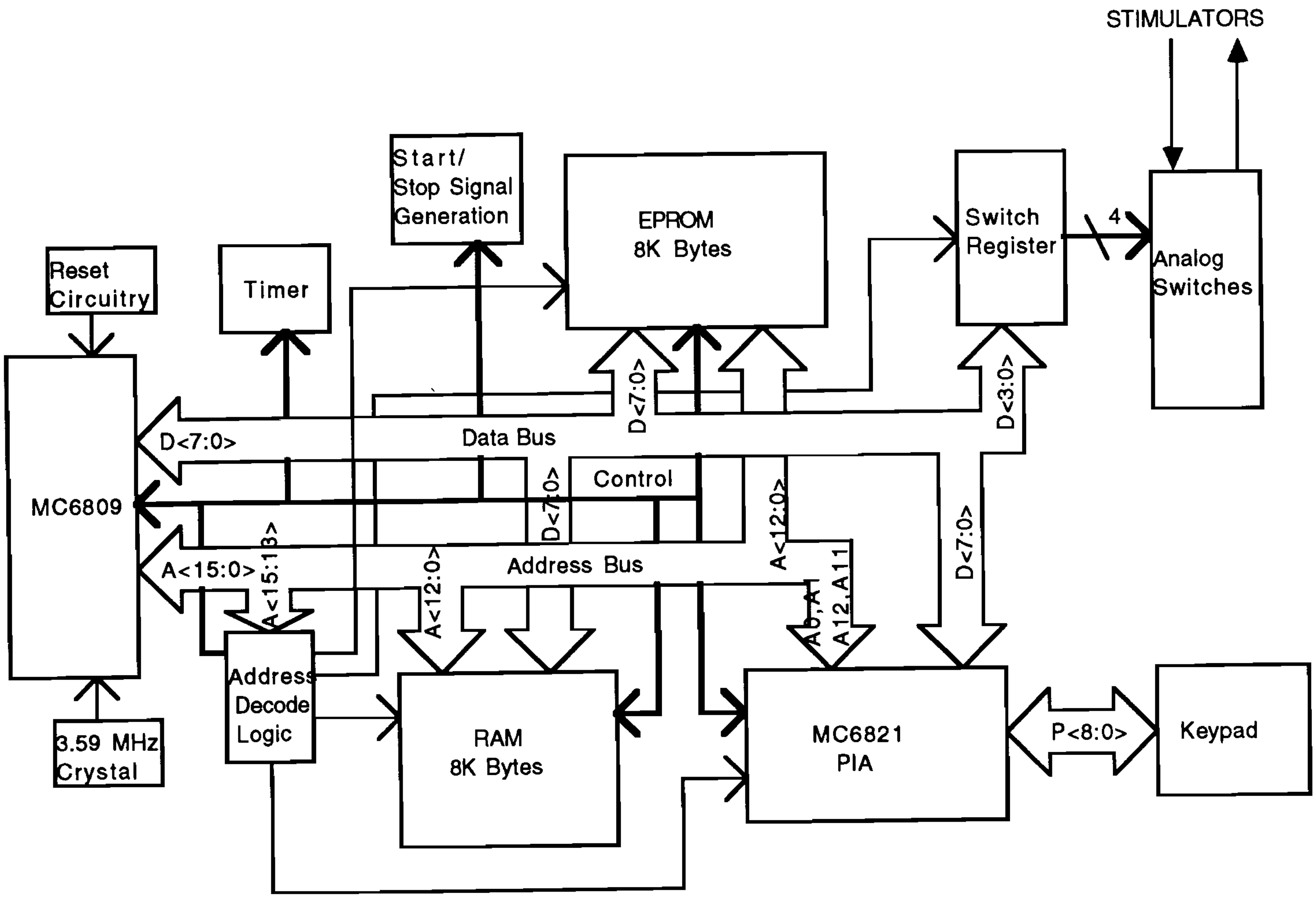


Figure 60 - Block Diagram

The MC6809 wrote to a register that drove the logical inputs for the LF13331. The programs controlling the CPU were burned into a 2764 8K x 8 EPROM. The microprocessor stored its data in a HM6264 8K x 8 static RAM. Both of these memories have fast enough access times to be compatible with the 6809 without the addition of wait states, yet they are quite inexpensive. Memories larger than actually required for this project were chosen to permit easy expansion.

Most of the user interface was supplied through a 20-button keypad. The operator could specify the desired switch and the corresponding on-off sequence. Every sequence could consist of up to 20 entries, each being any whole number of seconds in the range from 1-15. The 6821 PIA, a chip designed to be compatible with the 6809, provided the interfacing between the keypad and the CPU. A pushbutton wired to the 6809 allowed the user to start and stop the stimulation pattern. Another pushbutton enabled the resetting of the whole system. A complete circuit diagram and a list of parts appear in Appendix C.

The 16 address lines of the CPU correspond to a 64K memory space. The memory was divided into 8 8K-blocks by a 74LS138 3-to-8 decoder. Individual blocks were assigned to the RAM, PIA, register driving the switches, and EPROM. The memory map is outlined in figure 61.

8.4 Software

The controller operates as an interrupt-driven machine. Four interrupt lines feed into the MC6809: /RESET, /NMI, /FIRQ, and /IRQ. A falling edge in voltage in either of the first two signals or a low-

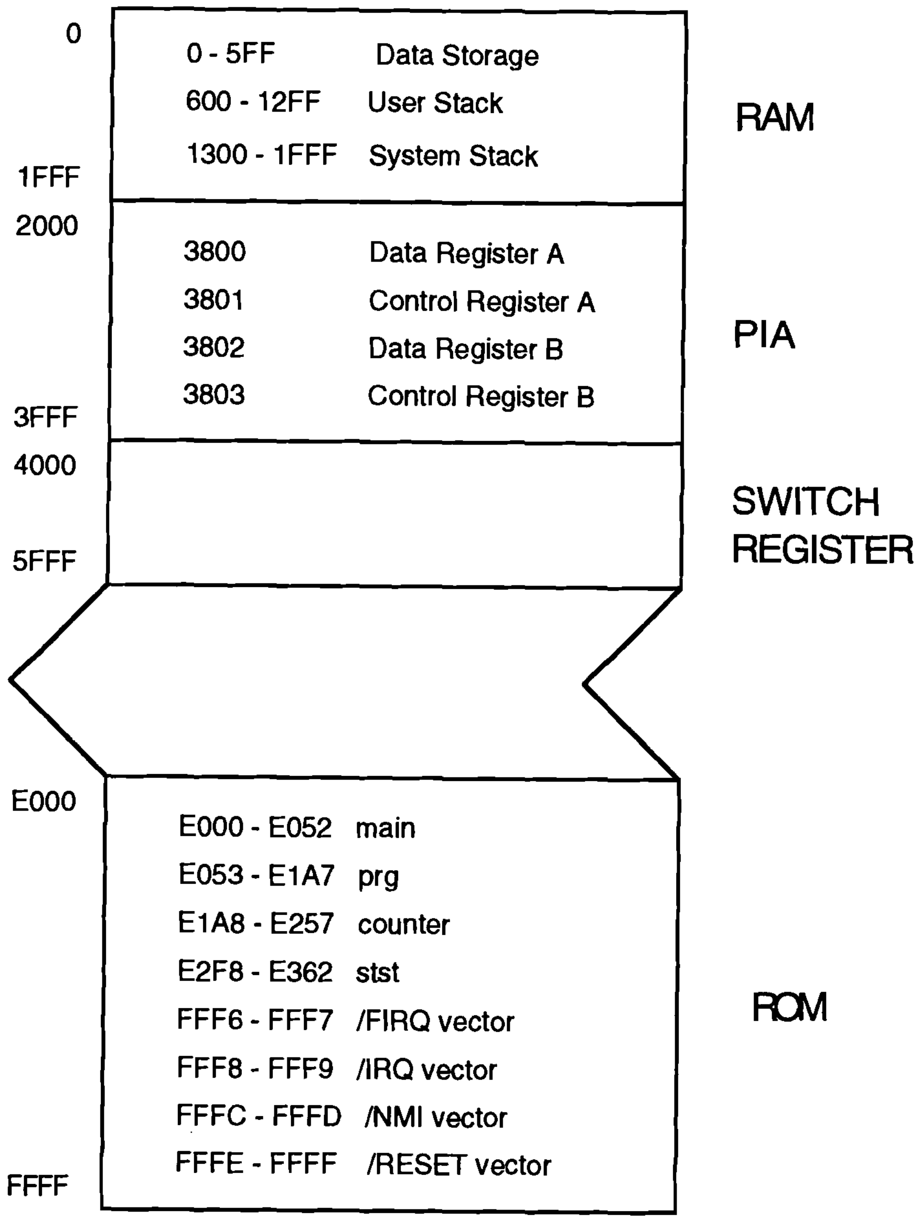


Figure 61 Device memory map

level voltage in either of the last two signals triggers an interrupt in the CPU provided that the condition code register, CCR, is set appropriately. /FIRQ and /IRQ requests may be masked by setting bits in the CCR. Upon receival of one of these four requests to communicate with the CPU, the 6809 jumps to the address specified by the appropriate interrupt vector and begins executing the software routine located there. These routines are stored in the EPROM.

An interrupt is generated on the /RESET pin on power-up or when the user depresses a certain pushbutton. The interrupt vector located in memory locations FFFE-FFFF points to the memory address of the start of the program driving the controller. In the program the stack pointers and a number of flags and registers are initialized. The CPU is then kept in an endless loop waiting to respond to other interrupt requests. This software is listed in Appendix C under the name main.o.

The interrupt masks and flags are initialized such that all the analog switches remain open until the user programs the desired timing sequence via the keypad. The keypad communicates with the CPU through the PIA. The PIA issues its requests to interact with the microprocessor on the /IRQ line. The /IRQ interrupt vector is located at FFF8-FFF9. The vector points to the interrupt-handling routine called prg.o in Appendix C.

Pressing the key labeled “PRG” begins the programming session. The user then pushes the key marked “NCH” to signal to the CPU that the next keypad entry will be the number of switches to be regulated. After giving the total number of desired switches, the operator next enters the number of the switch he wishes to program.

This number cannot be greater than the entry for the total number of switches. Programming always starts with the first off time. The succeeding on and off times for the switch are then entered. The CPU stores these times in the RAM. The sequencing alternates off, on, off, on, ... When the user wants to end programming for one switch, the person presses the key labeled "NXT." The user then enters the number of the next switch to be controlled. The same protocol previously outlined is followed for this and the other switches. Pushing the key marked "END" ends the programming. The mask for the /FIRQ interrupt is then cleared. Figure 62 provides an example of user programming entries and the corresponding responses of the switches and table 13 lists the order of the programming steps.

It is the user's responsibility to ensure that the timing sequence for each switch is of the same duration. The summation of the time entries for switch #1 determines the length of the total sequential pattern. If a sum for another switch is longer than this, that sequence will be cut off; if it is shorter, the switch will be toggled randomly.

The /FIRQ interrupt line is driven by a pushbutton. Depression of the pushbutton generates an interrupt request which is handled by the routine entitled stst.o in Appendix C. The vector pointing to this software is located in FFF6-FFF7. The interrupt either begins or ends the stimulation sequencing; the routine toggles the current state.

The primary step involved in starting or stopping the stimulation is to alter the software mask of the /NMI interrupt. The 6809 cannot prevent this interrupt request from being serviced as no

Key Sequence: PRG-NCH-3-1-10-3-5-2-NXT-3-4-4-4-4-4-NXT-2-10-10-END

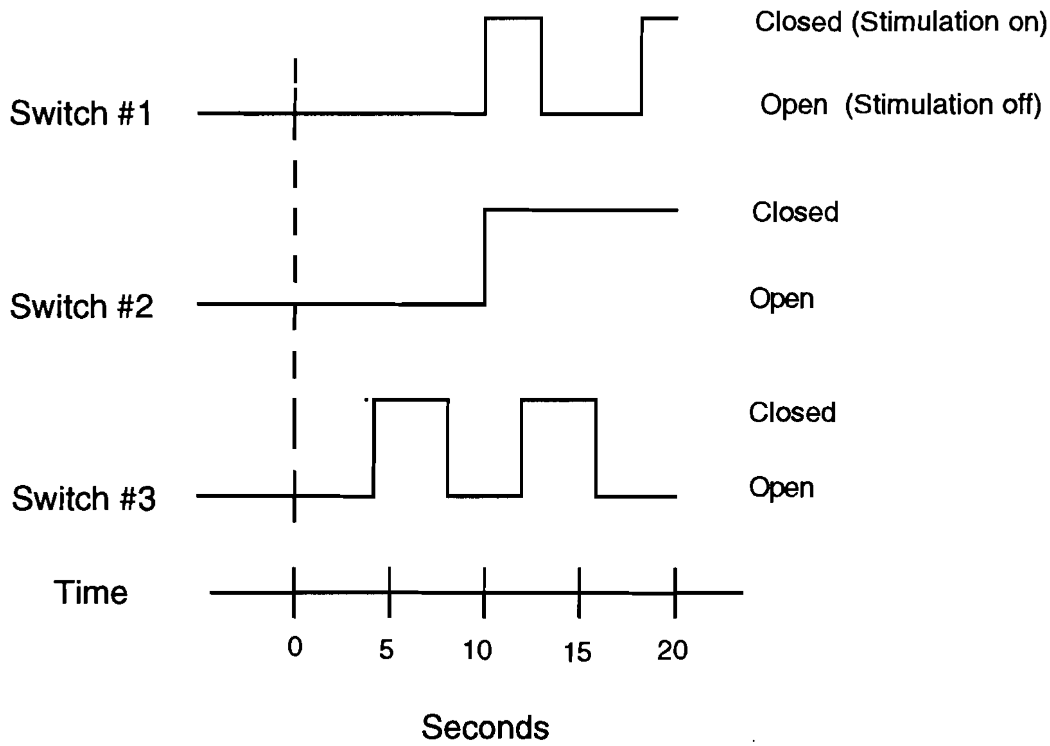


Figure 62 Sample sequence programming

Table 13 Programming steps

1. Press key "PRG" to begin programming
2. Press key "NCH" to enter number of switches
3. Enter number of switches to be used ($1 \leq$ num ≤ 4)
4. Enter switch number, n (n $\leq$ num)

Switch #n : 5. Enter off time (1-15)
6. Enter on time (1-15)

.

.

7. Press key "NXT" to end sequencing for switch
8. Enter new switch number, n2

Switch #n2 : 9. Enter off time (1-15)

.

.

10. Press key "END" to end the programming session

control bits exist to mask it. The interrupt must be handled every time it occurs. In the controller the /NMI line is connected to the output of Motorola's version of a '555 chip, which is wired in an astable configuration such that the chip serves as a clock with a frequency of 1 Hz. Thus, an interrupt is generated every second. The interrupts are handled by the routine named counter.o in Appendix C. The starting address of the program resides in the vector memory locations FFFC-FFFD. The software first checks to determine if a certain flag has been set. If the flag is clear then the routine is not executed. The flag is set by the /FIRQ interrupt routine when the user wants to start the stimulation and cleared when the user wants to stop the stimulation. This flag operates as a type of mask.

If the flag has been set, then the first on time for each switch being used is decremented upon the initial execution of the routine. For a given switch the on time is decremented by one after each succeeding interrupt until reaching zero. The switch is then opened and the countdown of the off-time register is begun. After this register reaches zero the switch is closed and the countdown of the next on-time register is started. This pattern continues until the end of the program sequence is reached. The end is demarcated by the end of the sequencing for the first switch. Therefore, the operator must make the sequence for each switch have the same time duration. Upon reaching the end the whole sequence is then restarted. This process continues until the user pushes a button to clear the masking flag.

8.5 Present State and Future Considerations

The controller was developed on a breadboard with the aid of the emulation capabilities offered by the HP64000 system. After successful testing the device was constructed on a perfboard using wire wrapping techniques. The software was burned into an EPROM, thereby allowing the controller to stand alone. Testing of the current version of the controller has shown that it does function properly. Excluding the power supply and the sockets, the parts cost a total of $39.18.

The next step is to employ the controller in clinical testing to ascertain if repetition of the desired movements really does help in improving volitional control.

A number of future additions to the controller would undoubtedly prove beneficial. An alphanumeric display would help the user keep track of the protocol for programming the device and the values which the person his entered. Options could be made available for varying the amplitude as well as the duration of the stimulation. Also, the size of the controller could probably be reduced by replacing the microprocessor with a microcontroller.

CHAPTER IX
CONCLUSIONS

9.1 Clinical Research

Considerable improvement in volitional function in the upper extremity affected by CP was quantified in all three subjects during the course of their FES programs. Due to the encouraging results all three boys chose to continue their stimulation therapy beyond the end of this study.

For this study D.S. underwent electrical stimulation of the extensors pollicis longus and brevis for 8 months and the abductor pollicis brevis for 7 months. His voluntary range of thumb extension increased by 35° while the range of thumb abduction showed no improvement. The advances in thumb extension enabled D.S. to properly perform the palmer pinch. Correct palmer pinch strength increased slightly from 2.9 lb. to 3.9 lb. Grip and lateral pinch forces demonstrated no amelioration, but this was somewhat anticipated as D.S. could generate these motions prior to beginning this study and and the associated muscle groups were not targeted for treatment.

Average times to complete the six dexterity tasks fell over the course of the FES program: from 72.4 sec. to 34.2 sec. for picking up five pens and placing them in a cup, from 207.4 to 41.2 sec. for lifting a quarter, dime, nickel, and penny out of a pan, from 9.7 to 7.0 sec. for lifting the lighter container, from 19.0 to 8.6 sec. for lifting the heavier can, and from 21.5 to 11.9 sec. for turning over five playing cards. Regression lines fitted to the log transformations of the times to completions vs. days of the FES program had negative slopes significant at p=.001 for five of the tests.

The number of seconds needed to finish the sixth task, lifting five balls out of a box, dropped from 17.7 to 12.2 before rising again to 15.7 on the final examination date of the study.

C.R. participated in the research for four months. In that period his ulnar wrist extensor was treated for 4 months, his thumb extensors and abductor for 2.5 months, and his finger flexors for 1.5 months. His voluntary wrist extension increased by 89°. Grip strength of the involved hand rose 1000% due to the attainment of the abilities to extend his wrist to a more mechanically advantageous position and to curl his fingers when the wrist was extended. Lateral pinch force climbed from 3 to 7 lb. while palmer pinch strength increased from 2 to 7 lb. before falling back to 5 lb.

Progress in manual dexterity enabled C.R. to switch from pinching with his first two fingers to pinching with his thumb and first two fingers. C.R. improved from not being able to pick up any of the coins in testing early in the study to being able to retrieve all the coins in examinations conducted near the end of the study. His average time to pick up the pens with the correct pinching motion decreased from 250.7 to 175.5 sec. and that for lifting the balls dropped from 63.7 to 36.2 sec.

M.E. was involved in the research for 3.5 months, during which he received FES of the extensor carpi ulnaris. Voluntary wrist extension increased 51° from 15° to 66°.

The force of his grip and lateral pinch remained unchanged; he was able to produce these movements with fairly good form even before starting electrical therapy. Average palmer pinch increased from 4.1 to 5.4 lb.

The duration necessary to pick up the pens fell from 119.1 to 35.3 sec. while that needed to retrieve the balls decreased from 28.8 to 20.9 sec. Regression lines fitted to the log transformation of the data had negative slopes statistically significant at p=.004. M.E. picked up the coins in 91.9 sec. at the end of the study while the task took him 121.5 sec. before the FES program.

The results of the stimulation of D.S.'s wrist extensor, which was continued from Mozelewski's work [7], were also encouraging. 9.5 months after the initiation of FES progress was still being made. By that juncture the 90° voluntary wrist extension D.S. exhibited with his involved hand had surpassed that of the uninvolved hand. Left wrist extension strength, as measured with a Cybex II machine, had continued to rise until reaching values 0.8 of those for the right wrist at speeds at or below 60°/sec. and almost half of the torques generated by the right arm at speeds at and above 120°/sec.

The results of terminating the stimulation of D.S.'s wrist extensor were inconclusive. The peak wrist extension remained at 90° and the scores for the dexterity tests continued to improve, but the Cybex data suggested a reduction in strength. However, the Cybex data was too variable and sparse to allow one to draw any firm conclusions.

It is difficult to determine exactly what physical changes led to the improvement in the three subjects. Hypertrophy of the muscles agonistic to a desired motion, reduction in the degree of spasticity of the muscles antagonistic to the movement, or better neural innervation of the agonist muscles may have facilitated voluntary function. This research did not differentiate the individual contributions of these three possibilities.

While definite progress was made during the FES programs, the advances cannot be unequivocally attributed solely to the electrical stimulation. Other factors may have played a part. Improvement may have taken place naturally as the boys matured. The baseline measurements in this research were not conducted over a long enough period of time to truly gauge the effects of maturing.

Amelioration in performing the tests may have resulted from the practice associated with repeating the tests over time. The dexterity data for the uninvolved hand of the subjects showed that the times needed to complete the tasks decreased as the study progressed. However, the percentage decreases were usually not as great as those for the involved hand. Table 14 summarizes these results.

Table 14 % decrease in time to complete a task between the scores at the beginning and end of the study

Subject	Task	Involved Hand	Uninvolved Hand
D.S.	Pick up pens	53%	19%
	Pick up coins	80%	42%
	Lift lighter can	28%	42%
	Lift heavier can	55%	22%
	Turn over cards	45%	22%
	Pick up balls	31%	13%
C.R.	Pick up pens	30%	20%
	Pick up balls	43%	23%
M.E.	Pick up pens	70%	10%
	Pick up balls	27%	29%
	Pick up coins	24%	19%

Advances may also have been due simply to renewed attention being paid to the affected limb. The subjects had a tendency to ignore their involved upper extremities before beginning the FES programs. The practice effects and refocusing of attention on the uninvolved limb were fringe benefits derived from the FES therapy, but they did muddle the answer to the question regarding the degree to which the electrical treatment itself improves function.

The FES therapy programs have had therapeutic effects in cerebral palsy children in four case studies conducted at OSU [4,7]. All four of these subjects exhibited spasticity. It is unknown if FES would be helpful in treating dyskinetic or ataxic children as well. C.R., the one subject who was also dystonic, was still hampered at the end of the study by recurring movements associated with that condition. The four subjects had normal intelligence, so they understood the purpose of the stimulation and could actively work with it. CP subjects with less comprehension may not benefit as greatly from the stimulation therapy or may not even tolerate it. The success of the treatment was also certainly dependent upon the very high motivation of the subjects and their parents. Still, the outcome of this clinical research holds promise that FES may become a viable option available at the discretion of medical personnel for the treatment of children with cerebral palsy.

9.2 Controller Research

The LF13331 JFET analog switch was successfully used to control the on and off sequencing of up to four stimulators. Pulse width modulation of the stimulator output was found to be possible, but was not implemented as part of the device built for this research.

The JFET switches were logically driven by a 6809 microprocessor. The user programmed the desired off-on patterns via a keypad. The controller repeated the patterns until the user requested stoppage. The sequence for any one switch could consist of up to 20 entries, each a whole number of seconds in the range from 1-15.

The device was built on a perfboard by employing wire wrapping techniques. It is easily portable and independent of all other devices except the stimulators. Preliminary testing has shown the controller to be operational, but the device has not yet been incorporated into an FES program. Seemingly, the controller could prove an integral part of the treatment of cerebral palsy children with functional electrical stimulation.

APPENDIX A
Data

D.S. Data

5/17

Measure	Left (Affected Side)	Right (Unaffected)
grip strength	1. 25 lb 2. 28 " 3. 28 "	1. 64 lb 2. 62 " 3. 64 "
palmer pinch strength (thumb curled under)	1. 2.5 lb 2. 2.0 " 3. 2.5 "	1. 14.0 lb 2. 14.0 " 3. 14.0 "
lateral pinch strength	1. 7.5 lb 2. 9.0 " 3. 7.0 "	1. 17.0 lb 2. 16.5 " 3. 17.0 "
thumb extension	-15°	
thumb abduction	28°	

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Measure	Left	Right
grip strength	1. 23 lb 2. 32 " 3. 31 "	1. 60 lb 2. 60 " 3. 63 "
palmer pinch strength (thumb curled under)	1. 3.0 lb 2. 4.0 " 3. 4.0 "	1. 13.0 lb 2. 12.5 " 3. 15.0 "
lateral pinch strength	1. 5.0 lb 2. 7.0 " 3. 5.0 "	1. 17.0 lb 2. 17.5 " 3. 15.0 "
thumb extension	-30°	
thumb abduction	32.5°	

7/3

Measure	Left	Right
grip strength	1. 27 lb 2. 22 " 3. 30 "	1. 67 lb 2. 59 " 3. 62 "
palmer pinch strength (thumb curled under)	1. 4.5 lb 2. 4.5 " 3. 4.0 "	1. 14.0 lb 2. 14.0 " 3. 12.0 "
lateral pinch strength	1. 8.0 lb 2. 9.0 " 3. 8.5 "	1. 16.0 lb 2. 17.5 " 3. 17.0 "
thumb extension	-15°	
thumb abduction	27°	

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Measure	Left	Right
thumb extension	-20°	
thumb abduction	30°	
wrist extension	69°	
lift lighter can (3 cycles)	1. 11.3 sec 2. 9.2 " 3. 8.5 "	1. 3.5 sec 2. 3.2 " 3. 3.0 "
lift heavier can (3 cycles)	1. 21.5 sec 2. 13.1 " 3. 16.2 "	1. 3.3 sec 2. 2.8 " 3. 3.1 "
pick 5 pens out of box and place in cup	1. 1:13.3 2. 1:02.7 3. 1:25.2	1. 7.0 sec 2. 9.0 " 3. 6.1 "
turn over 5 playing cards	1. 20.1 sec 2. 13.3 " 3. 14.3 "	1. 5.5 sec 2. 5.4 " 3. 4.0 "

pick quarter, dime, nickel and penny out of pan	1. 1:29.8 2. 4:20.0 3. did not finish	1. 10.3 sec 2. 6.3 " 3. 7.3 "

7/26

Measure	Left	Right
grip strength	1. 25 lb 2. 29 " 3. 35 "	1.70 lb 2. 68 " 3. 59 "
palmer pinch strength (thumb curled under)	1. 4.0 lb 2. 5.0 " 3. 5.0 "	1. 13.0 lb 2. 13.0 " 3. 13.0 "
lateral pinch strength	1. 6.0 lb 2. 5.0 " 3. 6.5 "	1. 17.0 lb 2. 16.0 " 3. 16.0 "
thumb extension	0°	
thumb abduction	25°	
wrist extension	52°	
lift lighter can	1. 11.0 sec 2. 8.0 " 3. 10.0 "	1. 6.5 sec 2. 5.0 " 3. 3.0 "
lift heavier can	1. 18.0 sec 2. 16.0 " 3. 29.0 "	1. 4.0 sec 2. 3.0 " 3. 3.0 "
pick up pens	1. 1:30.0 2. 1:05.0 3. 0:58.0	1. 6.0 sec 2. 5.0 " 3. 5.0 "
turn over playing cards	1. 33.0 sec 2. 17.0 " 3. 31.0 "	1. 5.0 sec 2. 4.5 " 3. 5.0 "
pick up coins	pulled coins up side of pan	1. 5.0 sec 2. 5.5 " 3. 6.0 "

8/15

Measure	Left	Right
thumb extension	5°	
thumb abduction	25°	
wrist extension	74°	
lift lighter can	1. 15.0 sec 2. 9.3 " 3. 14.9 "	1. 3.9 sec 2. 3.5 " 3. 3.2 "
lift heavier can	1. 14.4 sec 2. 20.8 " 3. 13.2 "	1. 3.1 sec 2. 3.3 " 3. 3.2 "
pick up pens	1. 1:40.3 2. 1:04.9 3. 0:45.9	1. 6.5 sec 2. 6.3 " 3. 6.1 "
turn over playing cards	1. 18.1 sec 2. 17.4 " 3. 14.6 "	1. 6.5 sec 2. 3.4 " 3. 3.9 "
pick up coins	1. 3:55.2 2. 1:45.5 3. 4:14.0	1. 8.6 sec 2. 8.9 " 3. 6.3 "

8/31

Measure	Left	Right
grip strength	1. 30 lb 2. 27 " 3. 25 "	1. 72 lb 2. 68 " 3. 58 "
palmer pinch strength (performed correctly)	1. 2.5 lb 2. 3.0 " 3. 4.0 "	1. 13.0 lb 2. 14.0 " 3. 13.0 "
lateral pinch strength	1. 5.0 lb 2. 7.5 " 3. 6.0 "	1. 17.0 lb 2. 17.0 " 3. 17.0 "
thumb extension	1. 4° 2. 8°	

thumb abduction	1. 28° 2. 30°	
wrist extension	1. 70° 2. 72°	
lift lighter can	1. 15.0 sec 2. 8.0 " 3. 14.0 "	1. 3.0 sec 2. 3.5 " 3. 2.5 "
lift heavier can	1. 16.0 sec 2. 27.0 " 3. 14.0 "	1. 3.0 sec 2. 2.5 " 3. 2.5 "
pick up pens	1. 1:33.0 2. 1:35.0 3. 1:02.0	1. 6.0 sec 2. 5.5 " 3. 5.0 "
turn over playing cards	1. 14.0 sec 2. 20.0 " 3. 17.0 sec	1. 6.0 sec 2. 5.0 " 3. 5.5 sec
pick up coins	1. 1:50.0 2. 0:45.0 3. 1:40.0	1. 5.5 sec 2. 7.0 " 3. 6.0 "

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<u>Measure</u>	<u>Left</u>	<u>Right</u>
grip strength	1. 25 lb 2. 26 " 3. 24 "	1. 66 lb 2. 61 " 3. 60 "
palmer pinch strength	1. 3.0 lb 2. 3.0 " 3. 2.0 "	1. 13.0 lb 2. 13.0 " 3. 12.5 "
lateral pinch strength	1. 6.0 lb 2. 4.5 " 3. 6.5 "	1. 15.5 lb 2. 15.0 " 3. 15.0 "
thumb extension	1. 10° 2. 10°	
thumb abduction	1. 28° 2. 25°	

wrist extension	1. 85° 2. 90°	
lift lighter can	1. 11.8 sec 2. 9.5 " 3. 14.4 " 4. 9.9 "	1. 2.9 sec 2. 3.0 " 3. 2.2 "
lift heavier can	1. 16.0 sec 2. 12.0 " 3. 11.0 "	1. 2.7 sec 2. 2.5 " 3. 3.0 "
pick up pens	1. 1:05.0 2. 1:52.3.0	1. 6.3 sec 2. 4.8 " 3. 4.8 " 4. 4.7 "
turn over playing cards	1. 15.4 sec 2. 15.9 " 3. 13.7 "	1. 7.0 sec 2. 5.1 " 3. 5.3 "
pick up coins	1. 3:47.5 2. 0:37.0 3. 1:07.0 4. 0:43.0	1. 4.9 sec 2. 5.0 " 3. 4.6 "

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<u>Measure</u>	<u>Left</u>	<u>Right</u>
thumb extension	1. 12° 2. 15°	
thumb abduction	1. 25° 2. 27°	
wrist extension	1. 90° 2. 95° 3. 95°	
lift lighter can	1. 9.8 sec 2. 9.3 " 3. 7.4 "	1. 2.5 sec 2. 2.5 " 3. 2.0 "
lift heavier can	1. 10.9 sec 2. 8.7 " 3. 7.4 "	1. 2.7 sec 2. 2.9 " 3. 3.0 "

pick up pens	1. 1:08.3 2. 0:39.3 3. 0:57.8	1. 4.5 sec 2. 5.2 " 3. 6.4 "
turn over playing cards	1. 8.6 sec 2. 9.5 " 3. 15.1 "	1. 3.9 sec 2. 3.7 " 3. 3.2 "
pick up coins	1. 0:27.8 2. 2:26.7 3. 1:20.0 4. 0:44.0	1. 5.8 sec 2. 4.6 " 3. 4.8 "
pick 5 balls out of box	1. 15.8 sec 2. 19.6 "	1. 4.8 sec 2. 5.2 "

<u>11/2</u>

<u>Measure</u>	<u>Left</u>	<u>Right</u>
grip strength (old gauge)	1. 26 lb 2. 26 " 3. 29 "	1. 63 lb 2. 64 " 3. 58 "
grip strength (new gauge)	1. 32 lb 2. 32 " 3. 33 "	1. 69 lb 2. 65 " 3. 65 "
palmer pinch strength (old gauge)	1. 4.0 lb 2. 3.0 " 3. 3.0 "	1. 12.0 lb 2. 12.5 " 3. 12.5 "
palmer pinch strength (new gauge)	1. 2.5 lb 2. 3.0 " 3. 4.0 "	1. 13.0 lb 2. 14.0 " 3. 15.0 "
lateral pinch strength (old gauge)	1. 4.5 lb 2. 6.0 " 3. 6.0 "	1. 15.0 lb 2. 14.5 " 3. 15.0 "
lateral pinch strength (new gauge)	1. 5.5 lb 2. 5.0 " 3. 6.5 "	1. 18.0 lb 2. 15.0 " 3. 16.0 "

thumb extension	1. 10° 2. 7° 3. 15°	
thumb abduction	1. 32° 2. 35° 3. 32°	
wrist extension	1. 80° 2. 85° 3. 85°	
lift lighter can	1. 10.1 sec 2. 7.9 " 3. 11.1 " 4. 8.1 "	1. 2.3 sec 2. 2.7 " 3. 2.5 "
lift heavier can	1. 9.2 sec 2. 16.1 " 3. 15.1 "	1. 3.1 sec 2. 3.5 " 3. 4.1 "
pick up pens	invalid - was standing	1. 5.9 sec 2. 5.7 " 3. 6.0 "
turn over playing cards	1. 14.1 sec 2. 9.7 " 3. 19.3 " 4. 11.3 "	1. 4.3 sec 2. 4.4 " 3. 4.2 "
pick up coins	1. 1:03.3 2. 1:03.8 3. 1:49.0 4. 0:54.5	1. 10.8 sec 2. 4.5 " 3. 5.3 "
pick up balls	1. 28.3 sec 2. 12.3 " 3. 16.2 " 4. 9.4 "	1. 4.5 sec 2. 4.4 " 3. 5.3 "

<u>11/13</u>

<u>Measure</u>	<u>Left</u>	<u>Right</u>
grip strength (new gauge)	1. 37 lb 2. 30 " 3. 27 " 4. 27 "	1. 80 lb 2. 74 " 3. 67 "

palmer pinch strength (new gauge)	1. 2.5 lb 2. 2.0 " 3. 2.5 "	1. 14.0 lb 2. 14.0 " 3. 13.0 "
lateral pinch strength (new gauge)	1. 7.5 lb 2. 7.5 " 3. 7.5 "	1. 17.0 lb 2. 17.0 " 3. 17.0 "
thumb extension	1. 3° 2. 2°	
thumb abduction	1. 22° 2. 20°	
wrist extension	1. 85° 2. 85° 3. 82°	
lift lighter can	1. 8.3 sec 2. 8.1 " 3. 9.0 "	1. 2.7 sec 2. 2.6 " 3. 2.4 "
lift heavier can	1. 16.0 sec 2. 8.5 " 3. 9.6 " 4. 7.8 5. 7.0	1. 2.3 sec 2. 2.3 " 3. 2.2 "
pick up pens	1. 54.1 sec 2. 25.7 " 3. 42.7 " 4. 48.4 "	1. 6.2 sec 2. 6.6 " 3. 4.7 " 4. 4.5 "
turn over playing cards	1. 10.5 sec 2. 10.4 " 3. 11.8 "	1. 3.4 sec 2. 3.7 " 3. 3.8 "
pick up coins	1. 0:37.4 2. 0:33.1 3. 1:07.0 4. 0:27.4	1. 7.7 sec 2. 6.3 " 3. 5.1 " 4. 5.5 sec
pick up balls	1. 18.5 sec 2. 15.9 " 3. 18.0 "	1. 4.4 sec 2. 4.3 " 3. 4.2 "

11/23

Measure	Left	Right
grip strength (old gauge)	1. 27 lb 2. 23 " 3. 24 "	1. 69 lb 2. 61 " 3. 56 "
grip strength (new gauge)	1. 21 lb 2. 28 " 3. 27 "	1. 69 lb 2. 70 " 3. 60 "
palmer pinch strength (old gauge)	1. 2.5 lb 2. 3.0 " 3. 3.0 "	1. 13.5 lb 2. 13.0 " 3. 12.5 "
palmer pinch strength (new gauge)	1. 3.0 lb 2. 3.0 " 3. 3.0 "	1. 15.0 lb 2. 14.0 " 3. 15.5 "
lateral pinch strength (old gauge)	1. 7.0 lb 2. 8.0 " 3. 5.5 "	1. 18.5 lb 2. 18.5 " 3. 17.0 "
lateral pinch strength (new gauge)	1. 6.0 lb 2. 4.5 " 3. 5.0 "	1. 18.0 lb 2. 17.5 " 3. 17.0 "
thumb extension	1. 10° 2. 7°	
thumb abduction	1. 25° 2. 27°	
wrist extension	1. 90° 2. 95°	
lift lighter can	1. 12.0 sec 2. 7.6 " 3. 7.3 " 4. 8.9 "	1. 2.2 sec 2. 2.1 " 3. 2.4 "
lift heavier can	1. 8.6 sec 2. 8.3 " 3. 8.4 "	1. 2.0 sec 2. 2.2 " 3. 1.8 "
pick up pens	1. 0:21.6 2. 1:13.0	1. 5.0 sec 2. 6.0 "

	3. 0:26.8	3. 5.7 "
	4. 0:45.3	
turn over playing cards	1. 12.0 sec	1. 3.5 sec
	2. 9.0 "	2. 3.8 "
	3. 11.0 "	3. 3.5 "
pick up coins	1. 0:48.2	1. 4.1 sec
	2. 1:24.2	2. 3.5 "
	3. 0:20.4	3. 4.9 "
	4. 0:33.0	
pick up balls	1. 16.2 sec	1. 4.0 sec
	2. 12.6 "	2. 3.9 "
	3. 10.9 "	3. 3.6 "
	4. 9.4 "	

<u>12/7</u>

<u>Measure</u>	<u>Left</u>	<u>Right</u>
grip strength	1. 29 lb	1. 60 lb
(new gauge)	2. 27 "	2. 60 "
	3. 33 "	3. 60 "
palmer pinch strength	1. 3.0 lb	1. 15.0 lb
(new gauge)	2. 5.0 "	2. 14.0 "
	3. 6.5 "	3. 14.0 "
	4. 6.5 "	
	5. 4.0 "	
lateral pinch strength	1. 7.0 lb	1. 18.0 lb
(new gauge)	2. 5.5 "	2. 16.5 "
	3. 6.5 "	3. 17.5 "
thumb extension	1. 15°	
	2. 16°	
thumb abduction	1. 30°	
	2. 30°	
wrist extension	1. 77°	
	2. 80°	
lift lighter can	1. 8.2 sec	1. 2.2 sec
	2. 8.7 "	2. 2.1 "
	3. 7.6 "	3. 1.9 "
lift heavier can	1. 8.4 sec	1. 1.8 sec
	2. 11.5 "	2. 3.0 "

	Left	Right
	3. 7.0 "	3. 2.0 "
	4. 7.6	
pick up pens	1. 27.4 sec	1. 4.8 sec
	2. 34.6 "	2. 5.3 "
	3. 31.4 "	3. 4.8 "
turn over playing cards	1. 12.2 sec	1. 3.3 sec
	2. 12.8 "	2. 3.6 "
	3. 14.0 "	3. 3.1 "
	4. 10.9 "	
	5. 11.8"	
pick up coins	1. 59.5 sec	1. 4.7 sec
	2. 37.5 "	2. 5.4 "
	3. 39.5 "	3. 4.3 "
	4. 33.6 "	
pick up balls	1. 11.6 sec	1. 5.0 sec
	2. 11.2 "	2. 3.9 "
	3. 13.7 "	3. 4.5 "

12/13

Measure	Left	Right
grip strength (new gauge)	1. 32 lb	1. 59 lb
	2. 32 "	2. 63 "
	3. 34 "	3. 65 "
palmer pinch strength (new gauge)	1. 5.0 lb	1. 14.5 lb
	2. 3.5 "	2. 13.0 "
	3. 3.5 "	3. 13.5 "
lateral pinch strength (new gauge)	1. 7.0 lb	1. 17.0 lb
	2. 6.5 "	2. 16.5 "
	3. 7.0 "	3. 17.5 "
thumb extension	1. 10°	
	2. 15°	
thumb abduction	1. 20°	
	2. 25°	
wrist extension	1. 90°	
	2. 90°	

lift lighter can	1. 7.6 sec 2. 7.2 " 3. 8.1 "	1. 2.1 sec 2. 2.1 " 3. 1.9 "
lift heavier can	1. 9.5 sec 2. 8.4 " 3. 7.8 "	1. 1.9 sec 2. 2.2 " 3. 3.3 " 4. 2.2 "
pick up pens	1. 27.6 sec 2. 41.8 " 3. 42.4 "	1. 6.2 sec 2. 5.2 " 3. 5.1 "
turn over playing cards	1. 13.8 sec 2. 10.4 " 3. 12.3 "	1. 3.8 sec 2. 4.2 " 3. 3.4 "
pick up coins	1. 0:39.6 2. 0:35.1 3. 1:03.9 4. 0:44.6	1. 4.3 sec 2. 4.2 " 3. 4.6 "
pick up balls	1. 12.4 sec 2. 7.0 " 3. 10.6 " 4. 10.9 "	1. 3.4 sec 2. 4.9 " 3. 4.1 "

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<u>Measure</u>	<u>Left</u>	<u>Right</u>
grip strength (new gauge)	1. 30 lb 2. 30 " 3. 25 "	1. 63 lb 2. 60 " 3. 56 "
palmer pinch strength (new gauge)	1. 3.0 lb 2. 5.5 " 3. 3.5 " 4. 3.0	1. 15.0 lb 2. 14.5 " 3. 13.0 "
lateral pinch strength (new gauge)	1. 9.0 lb 2. 5.5 " 3. 6.5 " 4. 7.5 "	1. 16.5 lb 2. 18.5 " 3. 17.5 "
thumb extension	1. 10° 2. 10°	

thumb abduction	1. 30° 2. 31°	
wrist extension	1. 87° 2. 88°	
lift lighter can	1. 6.4 sec 2. 6.5 " 3. 6.0 "	1. 2.7 sec 2. 2.8 " 3. 2.2 "
lift heavier can	1. 8.5 sec 2. 8.2 " 3. 9.0 "	1. 2.7 sec 2. 3.0 " 3. 2.4 "
pick up pens	1. 28.7 sec 2. 25.4 " 3. 35.1 "	1. 4.6 sec 2. 4.7 " 3. 5.1 "
turn over playing cards	1. 18.4 sec 2. 11.9 " 3. 11.2 " 4. 9.4 " 5. 8.0 "	1. 3.8 sec 2. 4.2 " 3. 3.4 "
pick up coins	1. 24.4 sec 2. 41.2 sec	1. 4.6 sec 2. 5.1 sec 3. 6.3 "
pick up balls	1. 17.1 sec 2. 12.0 " 3. 20.9 " 4. 12.9 " 5. 15.4 "	

D.S. Cybex Data

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Velocity	**Left Wrist**		**Right Wrist**		**Ratio: Left/Right**	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	8.2 ft-lb	5.0 ft-lb	11.0 ft-lb	16.4 ft-lb	.75	.30
15°/sec	8.1	8.6	12.9	17.7	.63	.49
30°/sec	5.1	8.1	12.5	18.3	.41	.44
60°/sec	6.0	9.3	14.0	19.9	.43	.47
120°/sec	3.8	8.5	14.2	21.5	.27	.40
180°/sec	0	3.5	13.2	19.2	0	.18
240°/sec	0	0	14.6	19.6	0	0

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Velocity	Left Wrist		Right Wrist		Ratio: Left/Right	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	6.0 ft-lb	1.7 ft-lb	11.7 ft-lb	12.2 ft-lb	.51	.14
15°/sec	8.5	2.5	10.0	18.5		
	7.0	4.5	10.3	13.0		
	6.5	6.8	10.6	13.5		
mean	7.3	4.6	10.3	15.0	.71	.31
std dev	1.0	2.2	0.3	3.0		
30°/sec	6.2	3.5	10.6	18.5		
	6.6	5.2	10.0	12.8		
	6.3	5.2	9.4	11.7		
mean	6.4	3.9	10.0	14.3	.64	.27
std dev	0.2	1.2	0.6	3.7		
60°/sec	5.4	3.5	11.0	17.5		
	4.9	4.5	11.0	17.5		
	5.0	5.0	11.0	17.5		
mean	5.1	4.3	11.0	17.5	.46	.25
std dev	0.3	0.8	0	0		
120°/sec	4.5	5.2	12.5	17.3		
	6.7	5.5	12.0	16.7		
	6.0	2.8	12.7	16.0		
mean	5.7	4.5	12.4	16.7	.46	.27
std dev	1.1	1.5	0.4	0.7		
180°/sec	1.5	2.8	12.8	17.1		
	3.0	1.7	13.1	16.9		
	1.2	2.1	12.7	17.0		
mean	1.9	2.2	12.9	17.0	.15	.13
std dev	1.0	0.6	0.2	0.1		
240°/sec	4.4	1.9	14.8	17.5		
	4.2	2.8	13.1	17.5		
	1.8	1.1	12.5	17.5		
mean	3.5	1.9	13.5	17.5	.26	.11
std dev	1.4	0.9	1.2	0		

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Velocity	**Left Wrist**		**Right Wrist**		**Ratio: Left/Right**	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	3.0 ft-lb	1.5 ft-lb	7.5 ft-lb	9.1 ft-lb	.40	.17
15°/sec	6.1	5.0	7.2	10.4		
	5.0	<u>5.0</u>	7.3	10.5		
	<u>6.0</u>		<u>8.6</u>	<u>8.3</u>		
mean	5.7	5.0	7.7	9.7	.74	.52
std dev	0.6	0	0.8	1.2		
30°/sec	6.0	3.7	7.0	9.5		
	6.0	2.5	8.0	9.9		
	<u>5.0</u>	<u>3.0</u>	<u>7.2</u>	<u>8.8</u>		
mean	5.7	3.1	7.4	9.4	.77	.33
std dev	0.6	0.6	0.5	0.6		
60°/sec	2.5	4.4	7.1	11.8		
	4.7	3.0	8.0	11.0		
	<u>3.0</u>	<u>2.0</u>	<u>6.8</u>	<u>9.5</u>		
mean	3.4	3.1	7.3	10.8	.47	.29
std dev	1.2	1.2	0.6	1.2		
120°/sec	2.1	1.2	7.8	11.0		
	<u>1.3</u>	1.2	6.7	11.5		
		<u>1.4</u>	<u>8.5</u>	<u>11.2</u>		
mean	1.7	1.3	7.7	11.2	.22	.12
std dev	0.5	0.1	0.9	0.3		
180°/sec	0.9	0.7	12.8	11.2		
	0.1	0	13.1	11.1		
	<u>0</u>	<u>0</u>	<u>12.7</u>	<u>11.0</u>		
mean	0.3	0.2	7.1	11.1	.04	.02
std dev	0.5	0.4	0.3	0.1		
240°/sec	0	0	7.1	11.7		
	0	0	7.2	11.6		
	<u>0</u>	<u>0</u>	<u>7.5</u>	<u>11.5</u>		
mean	0	0	7.2	11.6	0	0
std dev			0.2	0.1		

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Velocity	Left Wrist		Right Wrist		Ratio: Left/Right	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	3.8 ft-lb		6.3 ft-lb	9.0 ft-lb	.60	
15°/sec	5.2	6.2	7.2	11.0		
	5.0	5.9	7.5	10.9		
	3.0	5.1	8.3	9.5		
mean	4.4	5.7	7.7	10.5	.57	.54
std dev	1.2	0.6	0.6	0.8		
30°/sec	5.1	6.8	7.5	11.2		
	6.0	6.1	8.0	10.5		
	6.0	6.0	8.0	10.8		
mean	5.7	6.3	7.8	10.9	.73	.58
std dev	0.5	0.4	0.3	0.4		
60°/sec	6.3	7.0	7.8	10.2		
	5.2	7.5	8.0	10.1		
	5.1	7.2	7.8	9.0		
mean	5.5	7.2	7.9	9.8	.70	.73
std dev	0.7	0.3	0.1	0.7		
120°/sec	4.1	6.0	8.0	11.0		
	4.5	6.0	8.1	10.5		
	3.6	5.3	8.0	10.0		
mean	4.1	5.8	8.0	10.5	.51	.55
std dev	0.5	0.4	0	0.5		
180°/sec	1.8	3.3	8.1	12.0		
	0.9	5.8	9.0	11.0		
	3.0	3.7	7.0	10.0		
mean	1.9	4.3	8.0	11.0	.24	.34
std dev	1.1	1.3	1.0	1.0		
240°/sec	3.7	5.0	8.0	10.8		
	2.0	5.2	8.1	10.5		
	0	5.0	7.5	11.0		
mean	1.9	5.1	7.9	10.8	.24	.47
std dev	1.9	0.1	0.3	0.3		

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Velocity	Left Wrist		Right Wrist		Ratio: Left/Right	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	5.2 ft-lb	4.0 ft-lb	5.0 ft-lb	9.0 ft-lb	1.0	.44
15°/sec	5.5	5.8	6.8	8.9		
	5.2	6.3	8.1	10.9		
	6.3	5.7	7.3	8.5		
mean	5.7	5.9	7.4	9.4	.77	.63
std dev	0.6	0.3	0.7	1.3		
30°/sec	6.0	6.0	7.0	10.7		
	6.2	5.4	6.4	9.5		
	5.2	5.1	8.0	12.0		
mean	5.8	5.5	7.1	10.7	.82	.51
std dev	0.5	0.5	0.8	1.3		
60°/sec	6.1	6.1	7.0	12.0		
	6.0	6.0	8.0	12.0		
	6.0	5.9	8.0	13.0		
mean	6.0	6.0	7.6	12.3	.79	.49
std dev	0	0.1	0.6	0.6		
120°/sec	4.0	4.1	8.0	11.0		
	4.5	3.0	7.8	14.0		
	4.1	3.0	7.7	10.3		
mean	4.2	3.4	7.8	11.8	.54	.29
std dev	0.3	0.6	0.2	2.0		
180°/sec	3.5	1.4	7.2	11.8		
	3.1	3.7	6.5	12.5		
	3.0	3.0	7.0	10.5		
mean	3.2	2.7	6.9	11.6	.46	.23
std dev	0.3	1.2	0.4	1.0		
240°/sec	2.5	0.7	7.5	13.2		
	2.0	0	8.0	12.2		
	3.9	2.0	7.0	12.0		
mean	2.8	0.9	7.5	12.5	.37	.07
std dev	1.0	1.0	0.5	0.6		

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Velocity	Left Wrist		Right Wrist		Ratio: Left/Right	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	6.0 ft-lb		7.2 ft-lb	9.0 ft-lb	.83	
15°/sec	5.8	2.0	8.3	9.4		
	5.0	1.8	8.0	12.3		
	3.8	2.0	7.8	12.0		
mean	4.9	1.9	8.0	11.2	.61	.17
std dev	1.0	0.1	0.3	1.6		
30°/sec	5.0	1.5	8.0	10.2		
	5.0	2.0	7.8	12.8		
	0.5	4.0	7.0	9.0		
mean	3.5	2.5	7.1	10.7	.46	.23
std dev	2.6	1.3	0.8	1.9		
60°/sec	2.0	2.7	8.0	11.5		
	0.3	0.5	7.0	10.0		
	3.0	1.0	7.3	8.9		
mean	1.8	1.4	7.4	10.1	.24	.14
std dev	1.4	1.2	0.5	1.3		
120°/sec	3.0	0.5	8.5	12.2		
	1.5	1.0	7.5	11.6		
	1.2		7.7	11.3		
mean	1.9	0.8	7.9	11.7	.24	.06
std dev	1.0	0.4	0.5	0.5		
180°/sec	1.0	0	7.8	12.0		
	1.0	0	7.0	11.0		
	1.0	0	7.8	11.0		
mean	1.0	0	7.5	11.3	.13	0
std dev	0		0.5	0.6		
240°/sec	0.7	0	7.5	11.0		
	0.6	0	7.5	11.1		
	0.8	0	6.0	10.1		
mean	0.7	0	7.0	10.7	.10	0
std dev	0.1		0.9	0.6		

11/23

Velocity	Left Wrist		Right Wrist		Ratio: Left/Right	
	Ext	Flex	Ext	Flex	Ext	Flex
0°/sec	4.2 ft-lb		8.0 ft-lb	5.5 ft-lb	.53	
15°/sec	3.0	3.0	7.1	7.7		
	3.2	3.5	6.1	8.2		
	4.5	2.8	5.2	7.5		
mean	3.6	3.1	6.1	7.8	.59	.40
std dev	0.8	0.4	1.0	0.4		
30°/sec	3.2	5.0	6.8	8.0		
	3.1	3.2	6.1	7.0		
	3.0	2.8	6.2	10.5		
mean	3.1	3.7	6.4	8.5	.47	.44
std dev	0.1	1.2	0.4	1.8		
60°/sec	2.5	4.0	7.0	10.1		
	2.7	3.2	6.9	10.8		
	3.3	2.9	7.2	8.5		
mean	2.8	3.4	7.0	9.8	.40	.35
std dev	0.4	0.6	0.2	1.2		
120°/sec	2.9	2.5	6.8	9.6		
	3.2	2.0	7.0	8.0		
	3.5	1.5	6.5	7.5		
mean	3.2	2.0	6.8	8.4	.47	.24
std dev	0.3	0.5	0.3	1.1		
180°/sec	1.5	1.3	6.2	9.7		
	1.4	2.0	6.8	10.0		
	1.7	0.8	6.5	8.5		
mean	1.5	1.4	6.5	9.4	.23	.15
std dev	0.2	0.6	0.3	0.8		
240°/sec	5.0	1.5	4.9	7.9		
	4.0	1.2	4.0	9.0		
	2.0	0	6.5	9.0		
mean	3.7	0.9	5.1	8.6	.73	.10
std dev	1.5	0.8	1.3	0.6		

C.R. Data

8/27

Measure	Right (Affected Side)	Left (Unaffected Side)
grip strength (Lafayette dynamometer)	1. 0 kg 2. 0 " 3. 0 "	1.31 kg 2. 30.5 " 3. 24 "
wrist extension	1. -50° 2. -40° 3. -30°	1. 88° 2. 84° 3. 86°
thumb extension	1. 35° 2. 40° 3. 35°	
thumb abduction	1. 30° 2. 40° 3. 40°	

9/28

Measure	Right	Left
grip strength (Lafayette dynamometer)	1. 0 kg 2. 0 " 3. 0 "	1.43 kg 2. 40.5 " 3. 38.5 "
wrist extension	1. -30° 2. -15° 3. -15°	1. 67° 2. 70° 3. 68°
thumb extension	1. 70° 2. 80° 3. 75°	1. 80° 2. 80° 3. 77°
thumb abduction	1. 5° 2. 0° 3. 5°	1. 80° 2. 75° 3. 85°

10/6

Measure	Right	Left
grip strength (Stoelting dynamometer)	1. 2.0 kg 2. 2.0 " 3. 2.0 "	1.35.0 kg 2. 30.5 " 3. 27.5 "

wrist extension	1. -30° 2. -25° 3. -27°	1. 75° 2. 80° 3. 80°
thumb extension	1. 40° 2. 40° 3. 35°	1. 90° 2. 90° 3. 90°
thumb abduction	1. 45° 2. 45° 3. 45°	1. 80° 2. 80° 3. 75°
pick up pens (right hand pinching motion performed with digits 2&3)	1. 3:16.7 2. 2:47.2 3. 1:25.0	1. 9.1 sec 2. 7.0 " 3. 6.5 "
pick up coins (3:00 time limit) (right hand pinching performed with digits 2&3)	1. penny retrieved 2. quarter "	1. 7.2 sec 2. 5.4 " 3. 7.0 "

<u>10/13</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (Stoelting dynamometer)	1. 4.0 kg 2. 4.0 " 3. 2.5 "	1.39.0 kg 2. 32.0 " 3. 33.5 "
wrist extension	1. -5° 2. -3° 3. -4°	1. 85° 2. 85° 3. 85°
thumb extension	1. 75° 2. 65° 3. 65°	1. 90° 2. 90° 3. 90°
thumb abduction	1. 75° 2. 70° 3. 75°	1. 80° 2. 80° 3. 75°
pick up pens (right hand pinching motion performed with digits 2&3)	1. 1:24.1 2. 2:09.7 3. 0:53.6	1. 5.5 sec 2. 6.1 " 3. 5.3 "
pick up coins (3:00 time limit) (right hand pinching performed correctly)	1. nothing retrieved 2. " "	1. 5.6 sec 2. 5.7 " 3. 7.5 "

10/22

Measure	Right	Left
grip strength (Lafayette dynamometer)	1. 4.0 kg 2. 0 " 3. 0 "	1.33.0 kg 2. 31.0 " 3. 30.0 "
wrist extension	1. 0° 2. -1° 3. -4°	1. 75° 2. 80° 3. 82°
thumb extension	1. 60° 2. 65° 3. 65°	1. 75° 2. 75° 3. 75°
thumb abduction	1. 45° 2. 45° 3. 45°	1. 85° 2. 80° 3. 85°
pick up pens (right hand pinching motion performed correctly)	1. 4:15.3 2. 3:50.0 3. 3:06.0	1. 6.1 sec 2. 6.3 " 3. 5.3 "
pick up coins (3:00 time limit)	1. quarter 2. nothing	1. 7.0 sec 2. 6.3 " 3. 5.8
pick up balls	1. 1:09.0 2. 0:37.8 3. 0:36.9	1. 5.9 sec 2. 4.9 "

10/29

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 5 lb 2. 6 " 3. 14 " 4. 5 "	1. 86 lb 2. 80 " 3. 76 "
palmer pinch strength	1. 2.0 lb 2. 2.0 " 3. 2.0 "	1. 18.0 lb 2. 17.0 " 3. 17.5 "
lateral pinch strength	1. 3.5 lb 2. 2.0 " 3. 2.0 "	1. 18.0 lb 2. 14.5 " 3. 14.5 "

wrist extension	1. 5° 2. 15° 3. 12°	1. 70° 2. 75° 3. 80°
thumb extension	1. 75° 2. 80°	1. 85° 2. 90°
thumb abduction	1. 45° 2. 45°	1. 85° 2. 85°
pick up pens (trouble with thumb)	1. 3:48.9 2. 5:20.0 3. 4:44.0	1. 6.6 sec 2. 5.6 3. 5.2 "
pick up coins (3:00 time limit)	1. none	
pick up balls (trouble with thumb)	1. 1:49.8 2. 1:15.1 3. 0:53.4	1. 5.8 sec 2. 6.9 " 3. 5.3 "

<u>11/3</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer) (got thumb around gauge)	1. 15 lb 2. 25 " 3. 17 "	1. 89 lb 2. 83 " 3. 84 "
palmer pinch strength	1. 2.0 lb 2. 2.0 " 3. 2.0 "	1. 20.0 lb 2. 17.5 " 3. 18.0 "
lateral pinch strength	1. 5.5 lb 2. 4.5 " 3. 4.0 "	1. 14.5 lb 2. 14.0 " 3. 15.0 "
wrist extension	1. 5° 2. 0° 3. 10°	1. 80° 2. 85° 3. 80°
thumb extension	1. 65° 2. 70° 3. 65°	1. 82° 2. 82°
thumb abduction	1. 70° 2. 72°	1. 75° 2. 75°

pick up pens	1. 5:13.0 2. 3:11.0 3. 4:17.0	1. 5.3 sec 2. 5.2 3. 5.4 "
pick up coins (3:00 time limit)	1. quarter 2. none	1. 7.6 sec 2. 5.7 "
pick up balls	1. 0:46.4 2. 0:55.8 3. 1:01.0	1. 6.2 sec 2. 6.7 "

<u>11/11</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer)	1. 14 lb 2. 15 " 3. 25 " 4. 26 " 5. 17 "	1. 89 lb 2. 93 " 3. 90 "
palmer pinch strength	1. 3.0 lb 2. 2.0 " 3. 2.0 "	1. 18.5 lb 2. 18.0 " 3. 18.0 "
lateral pinch strength	1. 4.5 lb 2. 3.0 " 3. 4.5 "	1. 16.0 lb 2. 15.0 " 3. 15.5 "
wrist extension	1. 22° 2. 15° 3. 15°	1. 75° 2. 77°
thumb extension	1. 75° 2. 75°	1. 75° 2. 77°
thumb abduction	1. 67° 2. 67°	1. 85° 2. 85°
pick up pens	1. 6:47.0 2. 6:03.0	1. 5.1 sec 2. 4.7 " 3. 4.6 "
pick up coins (3:00 time limit)	1. none 2. quarter	1. 6.3 sec 2. 6.0 " 3. 5.8 "
pick up balls	1. 1:14.0 2. 0:29.9	1. 6.1 sec 2. 5.3 "

	3. 0:20.4 4. 0:47.7	3. 5.3 "

11/17

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 8 lb 2. 12 " 3. 14 " 4. 14 "	1. 94 lb 2. 80 " 3. 79 " 4. 74 "
palmer pinch strength	1. 1.5 lb 2. 3.5 " 3. 3.0 " 4. 4.0 "	1. 18.5 lb 2. 18.0 " 3. 18.0 "
lateral pinch strength	1. 3.0 lb 2. 3.0 " 3. 4.0 "	1. 15.0 lb 2. 18.5 " 3. 18.5 " 4. 18.5 "
wrist extension	1. 2° 2. 19° 3. 10°	1. 77° 2. 80°
thumb extension	1. 70° 2. 67°	1. 80° 2. 77°
thumb abduction	1. 67° 2. 70°	1. 80° 2. 85°
pick up pens	1. 2:15.1 2. 1:56.5 3. 2:55.3	1. 6.6 sec 2. 5.3 " 3. 5.5 "
pick up coins (3:00 time limit)	1. none 2. none 3. quarter	1. 6.5 sec 2. 5.1 " 3. 6.0 "
pick up balls	1. 31.3 sec 2. 39.0 " 3. 49.8 " 4. 27.9 " 5. 22.8 "	1. 4.5 sec 2. 4.0 " 3. 4.5 "

11/24

Measure	Right	Left
grip strength	1. 25 lb	1. 90 lb
(JAMAR dynamometer)	2. 27 "	2. 82 "
	3. 28 "	3. 77 "
palmer pinch strength	1. 4.0 lb	1. 19.0 lb
	2. 5.0 "	2. 19.5 "
	3. 5.0 "	3. 19.0 "
lateral pinch strength	1. 4.5 lb	1. 15.0 lb
	2. 5.0 "	2. 17.0 "
	3. 5.0 "	3. 16.0 "
wrist extension	1. 32°	1. 80°
	2. 36°	2. 75°
	3. 40°	3. 80°
thumb extension	1. 65°	1. 72°
	2. 70°	2. 75°
thumb abduction	1. 60°	1. 80°
	2. 57°	2. 75°
pick up pens	1. 6:50.0	1. 5.4 sec
	2. 3:52.7	2. 4.9 "
	3. 2:00.0	3. 5.4 "
pick up coins	1. quarter	1. 4.9 sec
(3:00 time limit)	2. quarter	2. 5.1 "
	3. quarter&nickel	3. 5.8 "
pick up balls	1. 0:42.0	1. 4.3 sec
	2. 1:25.3	2. 4.7 "
	3. 1:38.3	3. 4.1 "

12/2

Measure	Right	Left
grip strength	1. 17 lb	1. 92 lb
(JAMAR dynamometer)	2. 27 "	2. 83 "
	3. 21 "	3. 79 "
	4. 25 "	
palmer pinch strength	1. 7.0 lb	1. 19.0 lb
	2. 7.0 "	2. 19.5 "
	3. 6.5 "	3. 20.0 "

lateral pinch strength	1. 4.0 lb 2. 6.0 " 3. 5.0 "	1. 18.0 lb 2. 21.0 " 3. 20.0 "
wrist extension	1. 42° 2. 50° 3. 50°	1. 65° 2. 65°
thumb extension	1. 65° 2. 65°	1. 65° 2. 69°
thumb abduction	1. 75° 2. 30° 3. 35°	1. 75° 2. 77°
pick up pens	1. 4:44.8 2. 2:57.0 3. 3:58.0	1. 5.2 sec 2. 4.5 " 3. 5.2 "
pick up coins (3:00 time limit)	1. none 2. quarter&nickel 3. quarter	1. 5.0 sec 2. 6.4 " 3. 5.7 "

(forgot to bring balls)

<u>12/8</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer)	1. 28 lb 2. 20 " 3. 22 " 4. 21 "	1. 93 lb 2. 84 " 3. 79 "
palmer pinch strength	1. 8.0 lb 2. 6.0 " 3. 7.0 "	1. 19.0 lb 2. 18.0 " 3. 17.5 "
lateral pinch strength	1. 5.0 lb 2. 5.5 " 3. 6.0 "	1. 22.0 lb 2. 24.0 " 3. 24.0 "
wrist extension	1. 52° 2. 55° 3. 42° 4. 65°	1. 75° 2. 75°
thumb extension	1. 75° 2. 70°	1. 92° 2. 93°

thumb abduction	1. 35° 2. 40°	1. 82° 2. 55°
pick up pens	1. 5:16.8 2. 3:32.2 3. 2:12.3	1. 5.1 sec 2. 5.5 " 3. 4.7 "
pick up coins (3:00 time limit)	1. quarter 2. quarter&nickel 3. none	1. 5.1 sec 2. 5.8 " 3. 4.9 "
pick up balls	1. 1:36.7 2. 1:23.5 3. 1:04.6	1. 4.5 sec 2. 5.5 " 3. 4.4 "

<u>12/15</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer)	1. 28 lb 2. 25 " 3. 25 "	1. 106 lb 2. 101 " 3. 86 "
palmer pinch strength	1. 6.5 lb 2. 5.5 " 3. 5.5 "	1. 20.5 lb 2. 20.0 " 3. 18.0 "
lateral pinch strength	1. 5.0 lb 2. 5.0 " 3. 8.0 " 4. 7.0 "	1. 21.0 lb 2. 20.5 " 3. 21.5 "
wrist extension	1. 40° 2. 52° 3. 47°	1. 82° 2. 80°
thumb extension	1. 75° 2. 65°	1. 73° 2. 75°
thumb abduction	1. 70° 2. 70°	1. 80° 2. 85°
pick up pens	1. 2:44.0 2. 2:46.8 3. 0:51.5 4. 1:36.2	1. 4.3 sec 2. 5.3 " 3. 4.7 "

pick up coins (3:00 time limit)	1. none 2. quarter&nickel 3. none	1. 5.2 sec 2. 5.5 " 3. 4.6 "
pick up balls	1. 45.1 sec 2. 38.4 " 3. 50.6 "	1. 4.5 sec 2. 4.3 " 3. 5.1 "

1/6

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 17 lb 2. 15 " 3. 23 " 4. 19 "	1. 100 lb 2. 95 " 3. 80 "
palmer pinch strength	1. 5.5 lb 2. 4.5 " 3. 5.0 "	1. 20.0 lb 2. 18.0 " 3. 17.5 "
lateral pinch strength	1. 4.5 lb 2. 4.5 " 3. 5.5 "	1. 20.0 lb 2. 21.0 " 3. 21.0 "
wrist extension	1. 30° 2. 65° 3. 50° 4. 65°	1. 80° 2. 77°
thumb extension	1. 60° 2. 75° 3. 75°	1. 75° 2. 76°
thumb abduction	1. 52° 2. 55°	1. 65° 2. 68°
pick up pens	1. 2:09.5 2. 2:27.7 3. 4:09.9	1. 5.6 sec 2. 5.0 " 3. 5.7 "
pick up coins (3:00 time limit)	1. none 2. quarter 3. none	1. 5.6 sec 2. 5.2 " 3. 4.3 "
pick up balls	1. 1:02.2 sec 2. 0:42.9 "	1. 5.7 sec 2. 4.4 "

	3. 0:49.4"	3. 5.1 "
	4. 0:29.0	

<u>1/12</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer)	1. 23 lb 2. 23 " 3. 24 "	1. 81 lb 2. 80 " 3. 70 "
palmer pinch strength	1. 4.5 lb 2. 5.5 " 3. 5.0 "	1. 21.0 lb 2. 20.5 " 3. 20.0 "
lateral pinch strength	1. 4.5 lb 2. 5.0 " 3. 7.0 " 4. 9.0 5. 8.0	1. 19.0 lb 2. 19.0 " 3. 18.5 "
wrist extension	1. 51° 2. 65° 3. 67°	1. 85° 2. 87°
thumb extension	1. 65° 2. 67°	1. 80° 2. 82°
thumb abduction	1. 62° 2. 60°	1. 80° 2. 81°
pick up pens	1. 2:48.7 2. 1:14.0 3. 1:30.5 4. 1:43.3	1. 7.8 sec 2. 6.3 " 3. 5.0 " 4. 5.0 "
pick up coins (3:00 time limit)	1. quarter&nickel 2. quarter 3. quarter, nickel, & penny (dime retrieved at 7:00)	1. 5.3 sec 2. 4.3 " 3. 5.0 "
pick up balls	1. 52.9 sec 2. 44.5 " 3. 26.5 "	1. 4.0 sec 2. 3.9 " 3. 3.9 "

1/19

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 30 lb 2. 23 " 3. 22 "	1. 82 lb 2. 96 " 3. 90 "
palmer pinch strength	1. 6.0 lb 2. 5.0 " 3. 7.0 " 4. 6.0 "	1. 19.0 lb 2. 19.0 " 3. 20.0 "
lateral pinch strength	1. 7.0 lb 2. 5.5 " 3. 7.5 lb 4. 6.5 "	1. 21.5 lb 2. 19.0 " 3. 22.5 "
wrist extension	1. 55° 2. 57°	1. 80° 2. 75°
thumb extension	1. 67° 2. 70°	1. 77° 2. 77°
thumb abduction	1. 45° 2. 55° 3. 55°	1. 70° 2. 70°
pick up pens	1. 3:32.8 2. 1:46.9 3. 2:52.2 4. 1:21.5	1. 5.1 sec 2. 5.4 " 3. 4.7 "
pick up coins (3:00 time limit)	1. quarter,nickel,&penny 2. quarter&nickel 3. quarter, nickel, & penny (dime retrieved at 4:11)	1. 4.7 sec 2. 4.5 " 3. 6.2 " 4. 4.4 "
pick up balls	1. 47.4 sec 2. 44.7 " 3. 40.7 "	1. 5.0 sec 2. 4.0 " 3. 3.8 " 4. 4.1 "

1/27

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 25 lb 2. 21 " 3. 30 "	1. 96 lb 2. 85 " 3. 78 "

palmer pinch strength	1. 5.5 lb 2. 5.0 " 3. 5.0 "	1. 21.0 lb 2. 20.0 " 3. 19.0 "
lateral pinch strength	1. 6.5 lb 2. 8.0 " 3. 7.0 lb 4. 7.0 "	1. 20.5 lb 2. 20.5 " 3. 19.5 "
wrist extension	1. 57° 2. 55° 3. 63°	1. 80° 2. 82°
thumb extension	1. 67° 2. 65°	1. 77° 2. 75°
thumb abduction	1. 52° 2. 55°	1. 67° 2. 72°

<u>2 / 3</u>

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 24 lb 2. 30 " 3. 22 "	1. 92 lb 2. 88 " 3. 74 " 4. 80 "
grip strength (Lafayette dynamometer)	1. 5.0 kg 2. 5.5 " 3. 4.5 "	1. 41.5 kg 2. 38.0 " 3. 36.0 "
grip strength (Stoelting dynamometer)	1. 6.0 kg 2. 7.0 " 3. 7.5 "	1. 40.0 kg 2. 39.0 " 3. 35.0 "
palmer pinch strength	1. 4.5 lb 2. 4.0 " 3. 5.0 "	1. 23.0 lb 2. 22.0 " 3. 20.0 "
lateral pinch strength	1. 8.0 lb 2. 6.0 " 3. 6.0 "	1. 20.5 lb 2. 22.0 " 3. 21.0 "
wrist extension	1. 60° 2. 52° 3. 65°	1. 87° 2. 88°

thumb extension	1. 65° 2. 67°	1. 67° 2. 71°
thumb abduction	1. 35° 2. 35°	1. 76° 2. 77°
pick up pens	1. 2:56.3 2. 2:06.6 3. 1:24.5 4. 2:03.0	1. 4.0 sec 2. 3.9 " 3. 5.2 "
pick up coins (3:00 time limit)	1. quarter,nickel,&penny 2. quarter&nickel (penny &dime at 6:00) 3. quarter& nickel (penny at 4:45)	1. 5.4 sec 2. 4.8 " 3. 4.8 "
pick up balls	1. 31.9 sec 2. 21.9 " 3. 41.8 " 4. 28.2 " 5. 32.8 "	1. 3.8 sec 2. 3.9 " 3. 3.8 "

M.E. Data

9/28

Measure	Right (Affected Side)	Left (Unaffected Side)
grip strength (Lafayette dynamometer - grip span was too wide; inaccurate measure)	1. 0 kg 2. 1 " 3. 0 "	1.20.0 kg 2. 13.0 " 3. 15.0 "
wrist extension	1. -15° 2. -10° 3. -15°	1. 60° 2. 60° 3. 60°
thumb extension	1. 60° 2. 70° 3. 80°	1. 55° 2. 60°
thumb abduction	1. 50° 2. 65° 3. 60°	1. 50° 2. 45°

10/5

Measure	Right	Left
grip strength (Stoelting dynamometer)	1. 8.0 kg 2. 9.0 " 3. 5.5 "	1. 17.0 kg 2. 18.0 " 3. 18.0 "
wrist extension	1. -10° 2. -15° 3. -10°	1. 62° 2. 65° 3. 65°
thumb extension	1. 70° 2. 80° 3. 80°	1. 75° 2. 80° 3. 75°
thumb abduction	1. 55° 2. 60° 3. 55°	1. 80° 2. 80°
pick up pens	1. 3:14 2. 2:00	1. 10 sec 2. 8 "
pick up coins	1. 2:17 2. 1:46	1. 14 sec 2. 14 " 3. 12 "

10/13

Measure	Right	Left
wrist extension	1. 20° 2. 10° 3. 15°	1. 75° 2. 80° 3. 75°
thumb extension	85°	
thumb abduction	75°	
pick up pens	1. 1:35.4 2. 1:06.9	1. 9.1 sec 2. 7.5 "
pick up coins	1. 3:55.5 2. did not finish (> 5:00)	1. 12.7 sec 2. 11.8 " 3. 13.2 "

10/23

Measure	Right	Left
grip strength (Layfayette dynamometer - (smaller grip span than 9/28)	1. 4.0 kg 2. 3.5 " 3. 3.0 "	1. 12.0 kg 2. 12.0 " 3. 15.5 " 4. 14.0 " 5. 16.0 "
wrist extension	1. 45° 2. 50° 3. 45°	1. 50° 2. 55° 3. 55°
thumb extension	1. 60° 2. 60°	1. 80° 2. 77°
thumb abduction		1. 85° 2. 85°
pick up pens	1. 1:44.8 2. 1:05.2	1. 9.6 sec 2. 9.1 "
pick up coins	1. 2:03.9 2. 0:52.9 3. 0:51.4	1. 6.6 sec 2. 9.2 "
pick up balls	1. 27.3 sec 2. 27.2 "	1. 9.0 sec 2. 11.3 "

11/3

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 15 lb 2. 20 " 3. 14 "	1. 35 lb 2. 34 " 3. 35 "
palmer pinch strength	1. 3.0 lb 2. 5.0 " 3. 3.0 "	1. 11.5 lb 2. 12.5 " 3. 12.5 "
lateral pinch strength	1. 4.5 lb 2. 4.5 " 3. 5.0 "	1. 14.0 lb 2. 14.0 " 3. 14.0 "
wrist extension	1. 50° 2. 50° 3. 47°	1. 65° 2. 65°
thumb extension	1. 77° 2. 80°	1. 75° 2. 72° 3. 72°
thumb abduction	1. 90° 2. 90°	1. 85° 2. 85°
pick up pens	1. 1:12.4 2. 0:40.8 3. 0:39.7	1. 8.7 sec 2. 8.9 "
pick up coins	1. 5:08 2. 1:23 3. 5:16	1. 13.3 sec 2. 13.7 " 3. 12.5 "
pick up balls	1. 27.8 sec 2. 33.0 "	1. 16.0 sec 2. 9.6 "

11/21

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 14 lb 2. 11 " 3. 20 " 4. 15 " 5. 15 "	1. 35 lb 2. 36 " 3. 37 "
palmer pinch strength	1. 3.5 lb 2. 6.0 "	1. 13.5 lb 2. 15.0 "

	3. 4.5 "	3. 16.0 " 4. 12.0 lb
lateral pinch strength	1. 6.0 lb 2. 7.5 " 3. 5.5 "	1. 12.0 lb 2. 14.0 " 3. 13.5 "
wrist extension	1. 20° 2. 15° 3. 20°	1. 65° 2. 65° 3. 65°
thumb extension	1. 72° 2. 75°	1. 85° 2. 85°
thumb abduction	1. 60° 2. 60°	1. 75° 2. 70°
pick up pens	1. 1:21.0 2. 0:47.8 3. 0:40.2 4. 1:09.1	1. 15.1 sec 2. 9.2 " 3. 9.2 "
pick up coins	1. 4:13.9 2. 3:35.4	1. 7.7 sec 2. 10.6 "
pick up balls	1. 31.0 sec 2. 27.2 "	1. 10.6 sec 2. 13.4 " 3. 11.7 "

<u>12/7</u>

<u>Measure</u>	<u>Right</u>	<u>Left</u>
grip strength (JAMAR dynamometer)	1. 16 lb 2. 17 " 3. 15 "	1. 40 lb 2. 28 " 3. 35 " 4. 41 "
palmer pinch strength	1. 5.0 lb 2. 3.0 " 3. 4.0 "	1. 13.0 lb 2. 12.5 " 3. 12.5 "
lateral pinch strength	1. 4.0 lb 2. 6.0 " 3. 5.5 " 4. 5.0 "	1. 11.0 lb 2. 12.0 " 3. 14.0 " 4. 12.5 "
wrist extension	1. 45° 2. 55° 3. 55° 4. 56°	1. 62° 2. 66° 3. 65°

thumb extension	1. 85° 2. 85°	1. 85° 2. 80°
thumb abduction	1. 65° 2. 62°	1. 75° 2. 72°
pick up pens	1. 36.9 sec 2. 56.5 " 3. 54.1 " 4. 34.4 "	1. 9.7 sec 2. 7.4 " 3. 9.4 "
pick up coins	1. 6:06 2. 5:22	1. 13.8 sec 2. 11.4 " 3. 8.6 "
pick up balls	1. 23.3 sec 2. 18.5 " 3. 25.8 "	1. 8.6 sec 2. 8.2 "

1/11

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 22 lb 2. 20 " 3. 19 "	1. 47 lb 2. 41 " 3. 43 " 4. 45 "
palmer pinch strength	1. 5.0 lb 2. 3.0 " 3. 3.5 " 4. 4.5 "	1. 12.0 lb 2. 12.0 " 3. 14.0 "
lateral pinch strength	1. 5.0 lb 2. 4.5 " 3. 6.0 " 4. 7.5 "	1. 12.5 lb 2. 14.0 " 3. 12.0 "
wrist extension	1. 60° 2. 60°	1. 80° 2. 75°
thumb extension	1. 65° 2. 67°	1. 72° 2. 75°
thumb abduction	1. 65° 2. 62°	1. 75° 2. 72°

pick up pens	1. 32.9 sec 2. 39.7 " 3. 24.2 "	1. 6.9 sec 2. 7.0 " 3. 7.5 "
pick up coins	1. 3:02.3 2. 1:30.0 3. 1:34.4	1. 16.6 sec 2. 13.0 " 3. 10.5 "
pick up balls	1. 20.1 sec 2. 22.5 " 3. 28.1 "	1. 5.7 sec 2. 6.4 "

1/18

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 19 lb 2. 20 " 3. 23 "	1. 37 lb 2. 40 " 3. 35 "
palmer pinch strength	1. 6.0 lb 2. 5.5 " 3. 5.5 "	1. 12.0 lb 2. 12.0 " 3. 11.5 "
lateral pinch strength	1. 5.0 lb 2. 6.0 " 3. 8.0 " 4. 6.0 "	1. 11.0 lb 2. 11.0 " 3. 10.0 "
wrist extension	1. 60°	1. 67° 2. 70°
thumb extension	1. 85° 2. 90°	1. 75° 2. 75°
thumb abduction	1. 55° 2. 60°	1. 60° 2. 60°
pick up pens	1. 34.0 sec 2. 28.6 " 3. 35.0 "	1. 7.3 sec 2. 8.1 " 3. 7.2 "
pick up coins	1. 1:24.1 2. 3:05.1 3. 1:22.8	1. 9.6 sec 2. 14.1 " 3. 8.4 "
pick up balls	1. 25.1 sec 2. 22.0 " 3. 20.2 "	1. 7.0 sec 2. 9.8 " 3. 9.1 "

2 / 1

Measure	Right	Left
grip strength (JAMAR dynamometer)	1. 17 lb 2. 18 " 3. 19 " 4. 21 "	1. 35 lb 2. 32 " 3. 30 "
grip strength (Stoelting dynamometer)	1. 7.0 kg 2. 7.0 " 3. 7.0 "	1. 13.0 kg 2. 14.0 " 3. 15.0 "
palmer pinch strength	1. 6.0 lb 2. 5.0 " 3. 4.5 "	1. 14.0 lb 2. 12.0 " 3. 13.5 "
lateral pinch strength	1. 4.5 lb 2. 6.0 " 3. 5.5 "	1. 11.0 lb 2. 11.5 " 3. 12.0 "
wrist extension	1. 65° 2. 70° 3. 63°	1. 75° 2. 80°
thumb extension	1. 70° 2. 75°	1. 80° 2. 80°
thumb abduction	1. 55° 2. 60°	1. 65° 2. 67°
pick up pens	1. 49.4 sec 2. 38.8 " 3. 31.8 " 4. 29.7 "	1. 12.0 sec 2. 8.8 " 3. 6.6 "
pick up coins	1. 1:30.9 2. 1:03.7 3. 1:58.1	1. 11.6 sec 2. 10.3 " 3. 9.6 "
pick up balls	1. 15.4 sec 2. 29.4 " 3. 17.3 " 4. 16.6 "	1. 9.0 sec 2. 8.4 " 3. 5.8 "

APPENDIX B
Regression Analysis

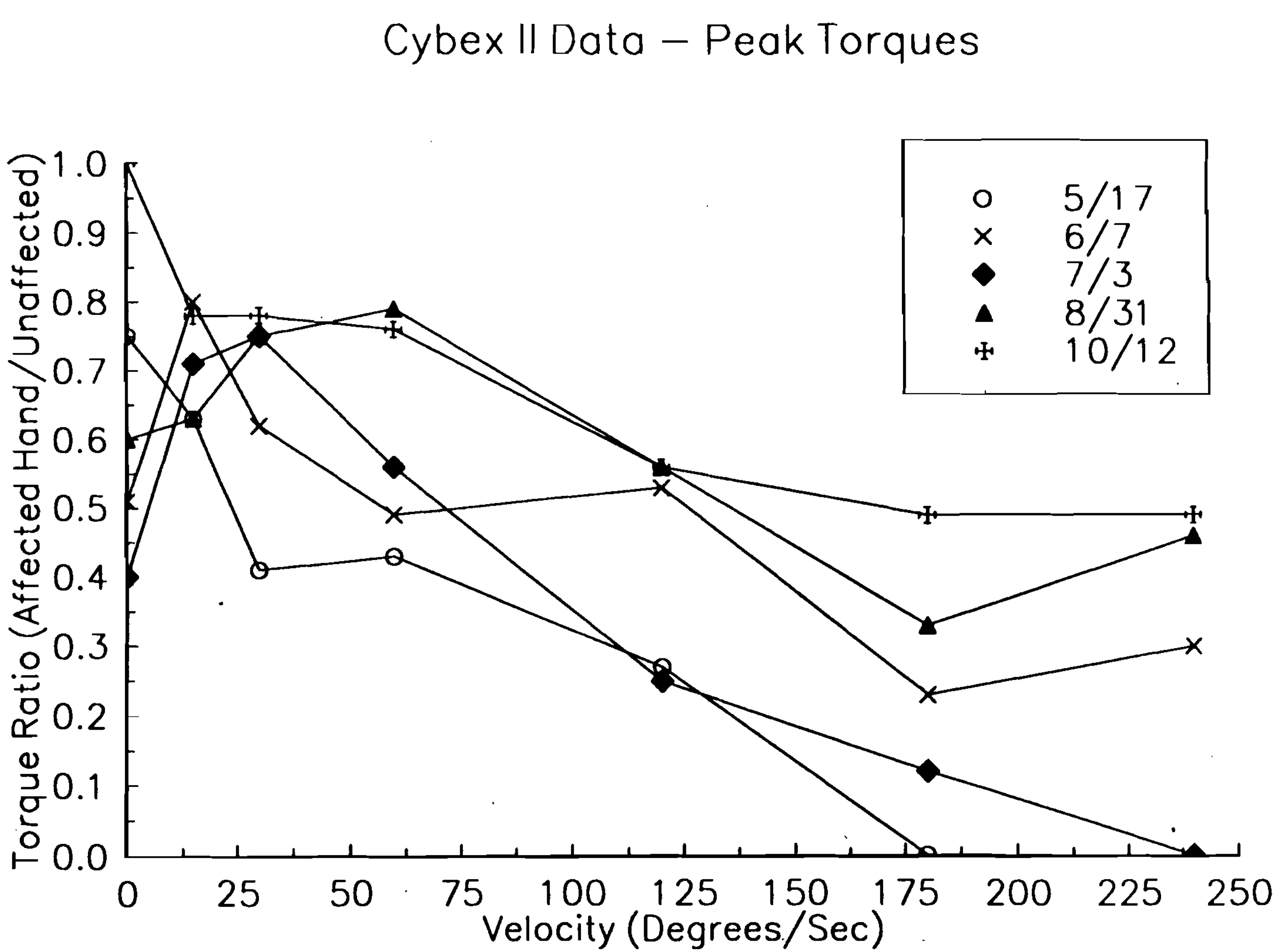


Figure 63 D.S. Cybex data - peak torque

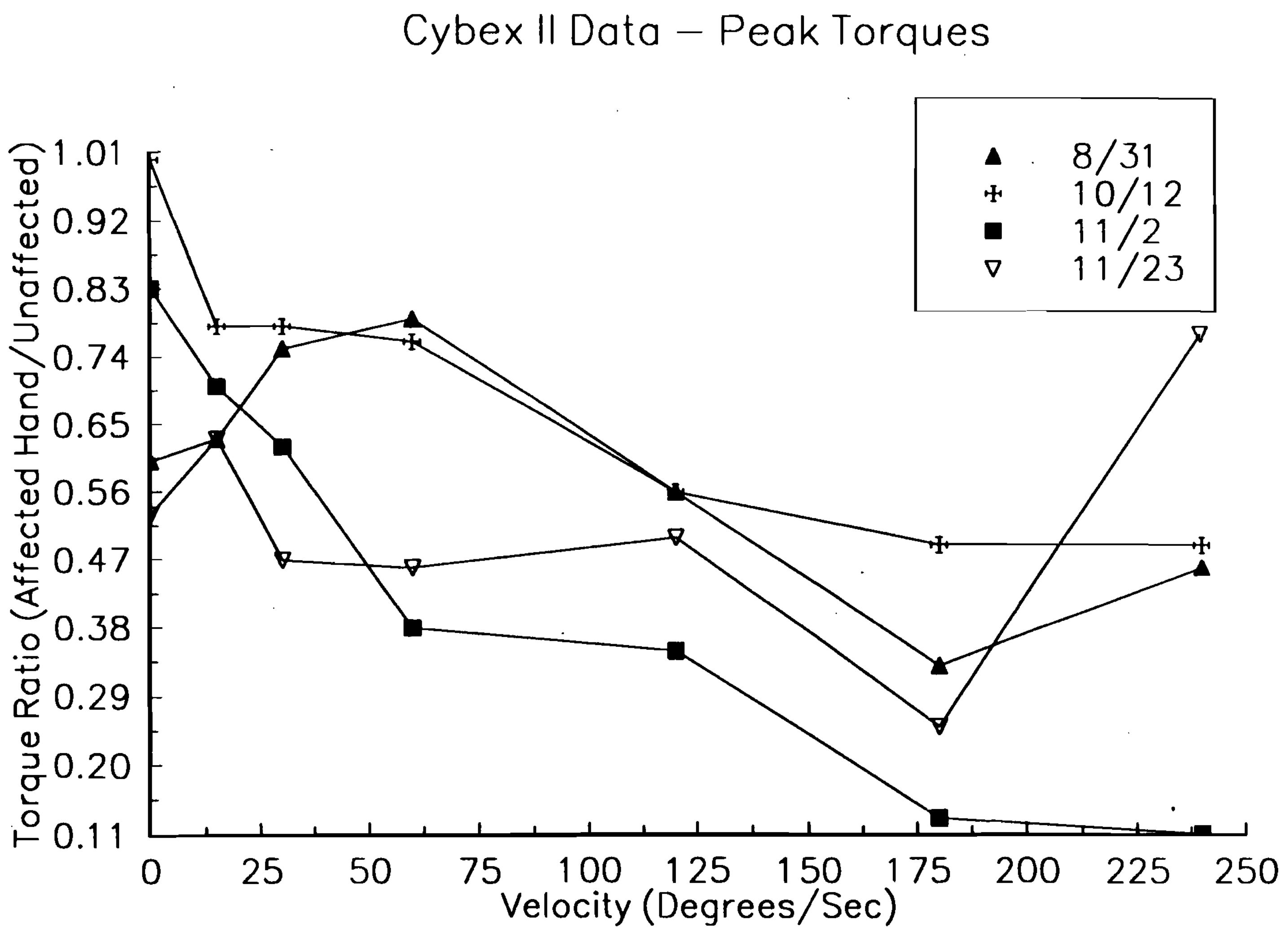


Figure 64 D.S. Cybex data - peak torque - after ending stimulation

```
MTB > regress c2 on 1 in c1;

SUBC> xlof;
SUBC> pure.

The regression equation is
llatplb = 6.71 - 0.00182 llatpd

Predictor        Coef        Stdev     t-ratio        p
Constant       6.7116       0.3711       18.08    0.000
llatpd      -0.001820     0.002589       -0.70    0.486

s = 1.259       R-sq = 1.2%       R-sq(adj) = 0.0%

Analysis of Variance

SOURCE        DF           SS           MS          F        p
Regression     1        0.783        0.783       0.49    0.486
Error         41       64.961        1.584
Total         42       65.744

Unusual Observations
Obs.  llatpd   llatplb       Fit  Stdev.Fit  Residual    St.Resid
 40      238     9.000     6.278      0.355     2.722       2.25R

R denotes an obs. with a large st. resid.
Possible lack of fit at outer X-values      (P = 0.017)
Overall lack of fit test is significant at P = 0.017

Pure error test - F = 2.51  P = 0.0269  DF(pure error) = 32

MTB > regress c15 on 1 in c10;
SUBC> xlof;
SUBC> pure.

The regression equation is
log(pps) = 0.798 + 0.00240 lppstd

Predictor        Coef        Stdev     t-ratio        p
Constant       0.7978       0.2089        3.82    0.001
lppstd       0.002397     0.001237        1.94    0.062

s = 0.2786      R-sq = 10.8%      R-sq(adj) = 7.9%

Analysis of Variance

SOURCE        DF           SS           MS          F        p
Regression     1      0.29141      0.29141       3.75    0.062
Error         31      2.40623      0.07762
Total         32      2.69763

Unusual Observations
Obs.  lppstd  log(pps)       Fit  Stdev.Fit  Residual    St.Resid
 24      182    1.8718    1.2340     0.0532    0.6378       2.33R
 25      182    1.8718    1.2340     0.0532    0.6378       2.33R
```

R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 4.00 P = 0.0060 DF(pure error) = 25

MTB > plot c16 vs. c10

```
ppvar    -                                   2
         -
         -
      1.5+  *                                *
         -                                     *               *
         -                       2
         -                                   *
         -  *
      0.0+              2                    2
         -  *                    3      5                      *
         -                                   *
         -                       *   2  *                      2
         -
     -1.5+              *
         -                           *
         -
          ----+---------+---------+---------+---------+---------+--lppstd
             90        120       150       180       210       240
```

MTB > nscores of c16 put into c22
MTB > plot c22 vs. c16

```
C22      -
         -
         -                                                       2
      1.5+                                             *
         -                                           2
         -                                     2    *
         -                               * *
         -                          4
      0.0+                      * 3
         -                     5
         -               *    2
         -              2
         -             3
     -1.5+
         -       *
         -    *
         -
          ------+---------+---------+---------+---------+---------+ppvar
            -1.60     -0.80      0.00      0.80      1.60      2.40
```

Figure 65 D.S. left palmer pinch residuals

```
MTB > correlation between c22 and c16

Correlation of C22 and ppvar = 0.972

MTB > regress c51 on 1 in c50;
SUBC> xlof;
SUBC> pure.

The regression equation is
lgrpstlb = 27.4 + 0.00600 lgrpstd

Predictor        Coef        Stdev     t-ratio        p
Constant       27.357        1.195       22.89    0.000
lgrpstd      0.005996     0.007432        0.81    0.424

s = 3.657        R-sq = 1.6%        R-sq(adj) = 0.0%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1        8.71        8.71      0.65    0.424
Error         41      548.41       13.38
Total         42      557.12

Unusual Observations
Obs. lgrpstd  lgrpstlb       Fit Stdev.Fit  Residual    St.Resid
 12       71    35.000    27.782     0.769     7.218       2.02R
 25      181    37.000    28.442     0.628     8.558       2.38R
 32      191    21.000    28.502     0.665    -7.502      -2.09R
R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.83  P = 0.0962  DF(pure error) = 31
```

```
SUBC> xlof;
SUBC> pure.

The regression equation is
log(plc) = 3.10 - 0.00361 lplcrdd

Predictor        Coef        Stdev     t-ratio       p
Constant      3.09522      0.09112       33.97   0.000
lplcrdd    -0.0036079    0.0006090       -5.92   0.000

s = 0.2251       R-sq = 48.0%      R-sq(adj) = 46.6%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      1.7789      1.7789     35.10    0.000
Error         38      1.9258      0.0507
Total         39      3.7047

Unusual Observations
Obs. lplcrdd  log(plc)        Fit Stdev.Fit  Residual    St.Resid
  4       48    3.4965     2.9220    0.0652    0.5745       2.67R
  6       48    3.4340     2.9220    0.0652    0.5119       2.38R
 16      137    2.1518     2.6009    0.0356   -0.4492      -2.02R
R denotes an obs. with a large st. resid.

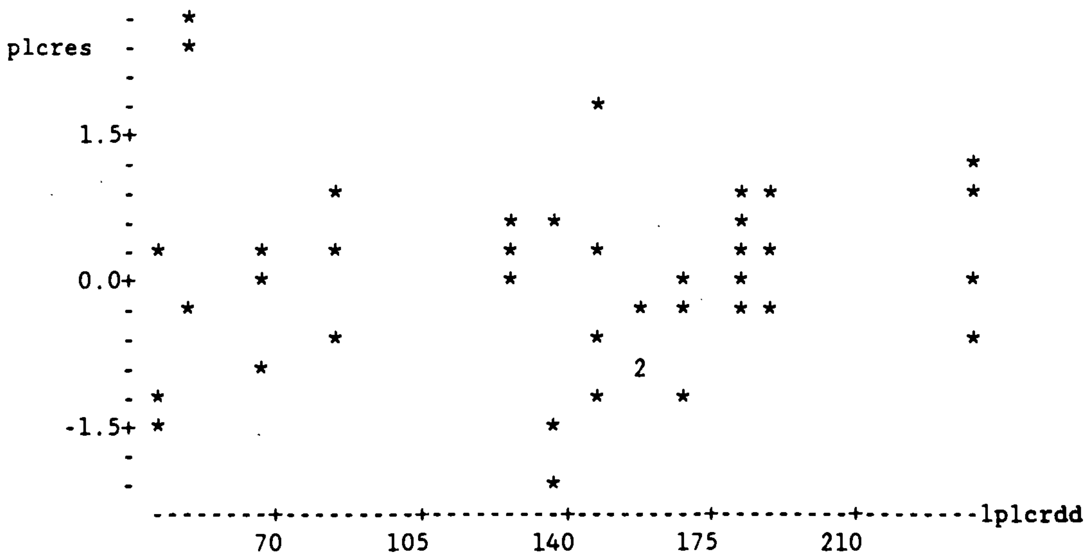
No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.92  P = 0.0840  DF(pure error) = 28


MTB > print c9

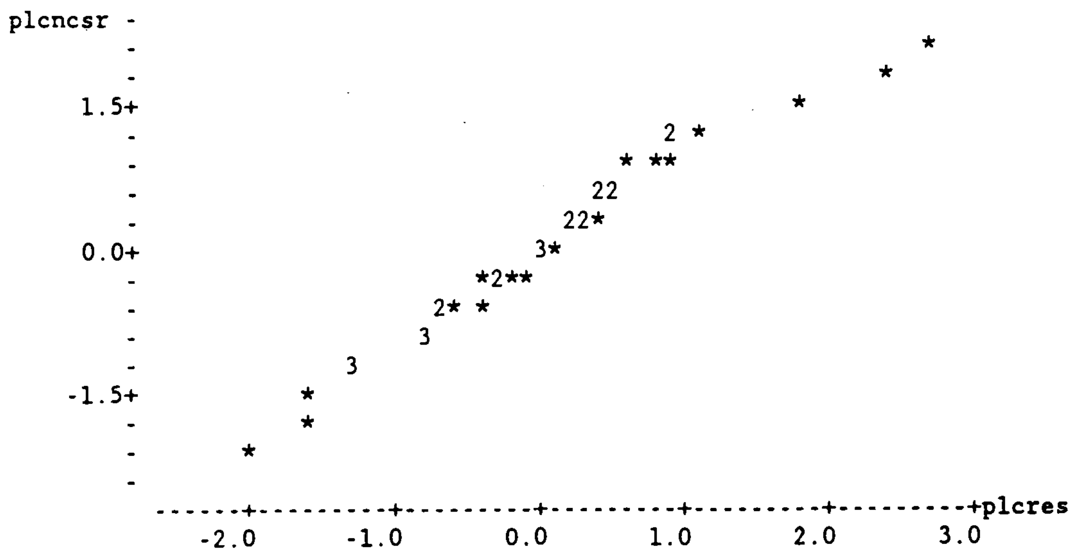
plccookd
  0.003978   0.134331   0.084737   0.325685   0.007788   0.258652   0.001435
  0.000029   0.019320   0.011729   0.020734   0.000843   0.002377   0.004273
  0.000146   0.052360   0.031727   0.003358   0.001760   0.022822   0.041599
  0.005224   0.008833   0.009833   0.000953   0.000006   0.028414   0.002775
  0.001660   0.005166   0.016895   0.001044   0.000366   0.020229   0.002647
  0.004025   0.068902   0.038487   0.000021   0.029532
```

```
MTB > plot c7 vs. cl
```




```
MTB > nscores of c7 put into c59
MTB > name c59 'plcncsr'

MTB > plot c59 vs. c7
```




```
MTB > correlation between c59 and c7

Correlation of plcncsr and plcres = 0.986
```

Figure 66 D.S. - left hand - playing card residuals

```
SUBC> xlof;
SUBC> pure.

The regression equation is
log(cns) = 5.54 - 0.00991 lqdnpd

Predictor        Coef        Stdev     t-ratio        p
Constant       5.5428       0.2486       22.30    0.000
lqdnpd      -0.009908     0.001669       -5.94    0.000

s = 0.5118      R-sq = 48.8%     R-sq(adj) = 47.4%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      9.2376      9.2376     35.26    0.000
Error         37      9.6935      0.2620
Total         38     18.9311

Unusual Observations
Obs.  lqdnpd  log(cns)       Fit Stdev.Fit  Residual    St.Resid
 10      126    5.4272    4.2944    0.0855    1.1327       2.24R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

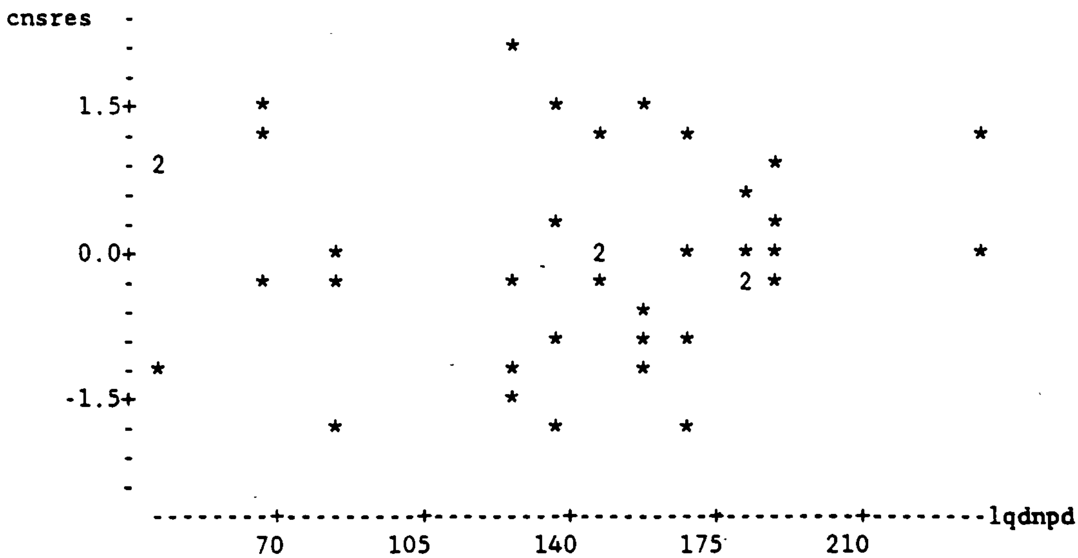
Pure error test - F = 0.51  P = 0.8568  DF(pure error) = 28


MTB > print c18

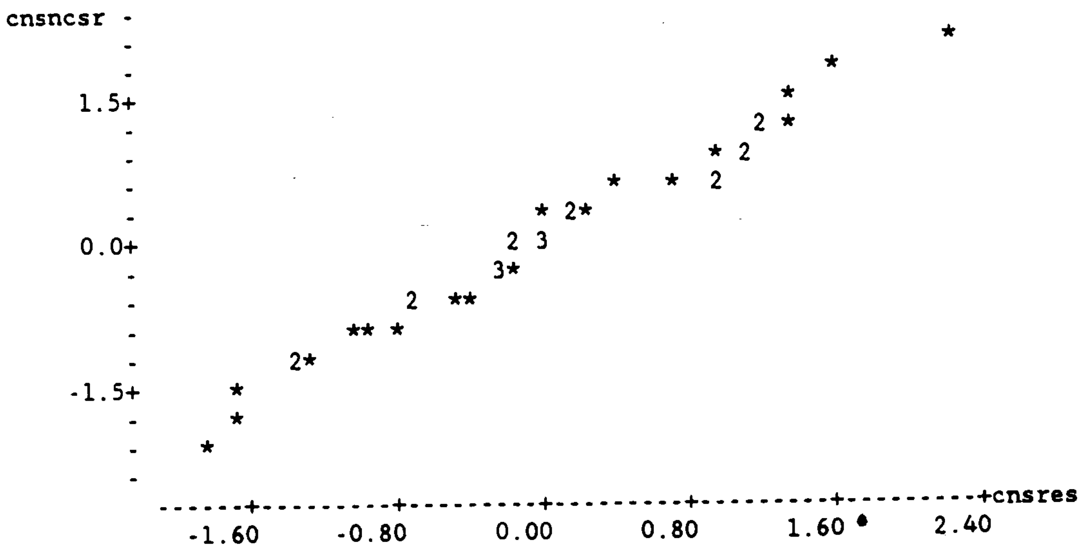
cnscookd
  0.121888   0.062634   0.071253   0.008187   0.064672   0.082586   0.000013
  0.105358   0.001433   0.072348   0.026344   0.000454   0.016033   0.038380
  0.033424   0.002003   0.008347   0.000199   0.000253   0.019199   0.000408
  0.007385   0.013327   0.028229   0.025953   0.000001   0.021139   0.051102
  0.010007   0.010975   0.001215   0.000366   0.004633   0.000000   0.001554
  0.023797   0.001445   0.000031   0.090009

MTB > regress c6 on 1 in c1;
```

MTB > plot c16 vs. c10



MTB > plot c19 vs. c16



MTB > correlation between c19 and c16

Correlation of cnsncsr and cnsres = 0.990

Figure 67 D.S. - left hand - coins residuals

```
MTB > regress c25 on 1 in c20;

SUBC> xlof;
SUBC> pure.

The regression equation is
log(pen) = 4.64 - 0.00548 lpensd

Predictor        Coef        Stdev     t-ratio        p
Constant       4.6363       0.1332       34.81    0.000
lpensd     -0.0054796    0.0009130       -6.00    0.000

s = 0.3199      R-sq = 53.0%     R-sq(adj) = 51.5%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1      3.6858      3.6858     36.02    0.000
Error        32      3.2744      0.1023
Total        33      6.9602

Unusual Observations
Obs.  lpensd  log(pen)       Fit  Stdev.Fit  Residual    St.Resid
 14      126    4.7212    3.9459     0.0552    0.7753       2.46R
 22      168    3.0727    3.7157     0.0635   -0.6430      -2.05R

R denotes an obs. with a large st. resid.

Lack of fit test
Possible curvature in variable lpensd (P = 0.043)
Overall lack of fit test is significant at P = 0.043

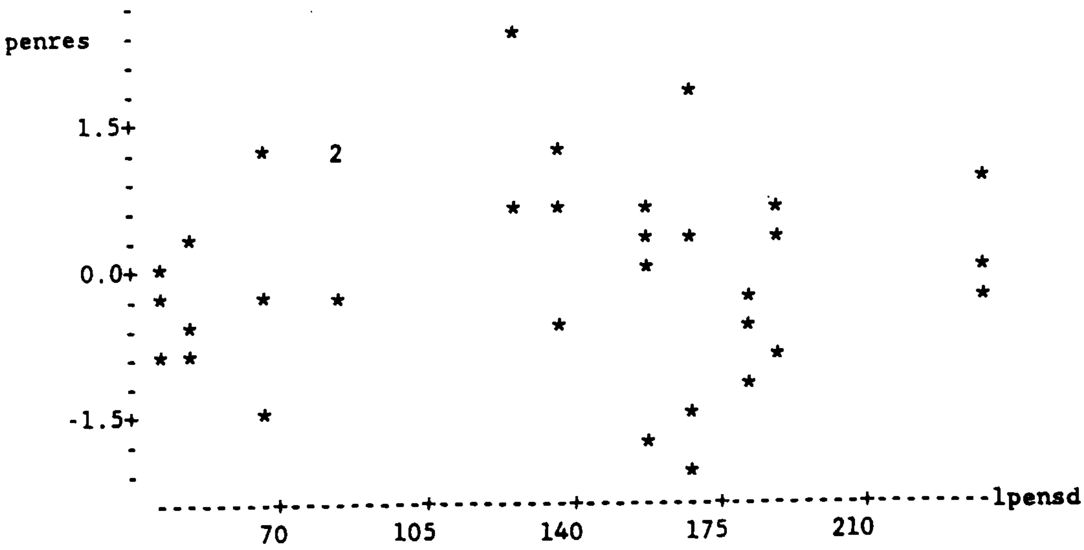
Pure error test - F = 1.08  P = 0.4158  DF(pure error) = 23


MTB > print c28

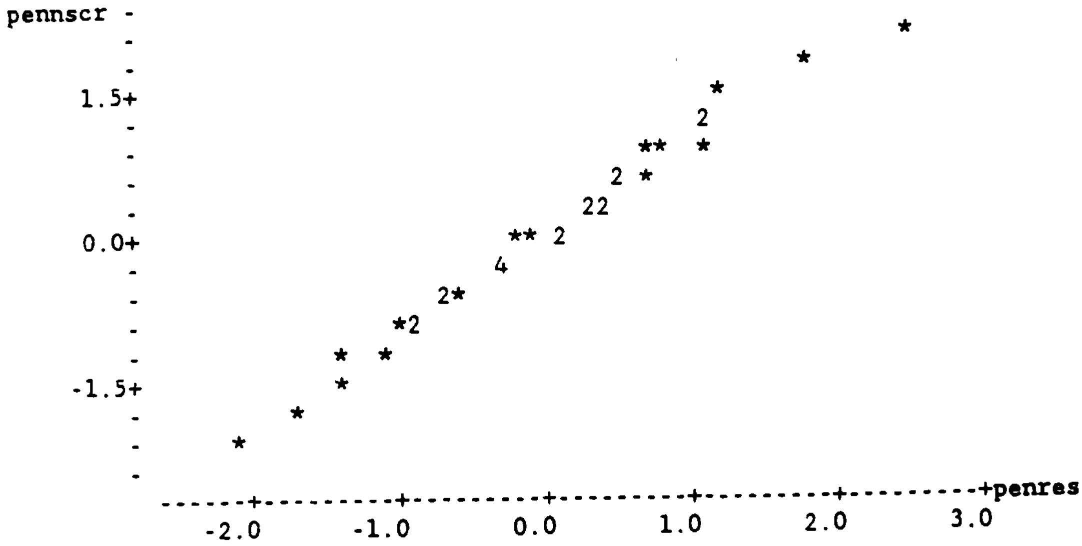
pencookd
  0.0064071   0.0391538   0.0011183   0.0082990   0.0205024   0.0507241
  0.0421863   0.0029331   0.0679553   0.0336073   0.0377376   0.0006313
  0.0080801   0.0930045   0.0175470   0.0070443   0.0045037   0.0087858
  0.0497023   0.0000482   0.0021499   0.0863286   0.0689674   0.0381240
  0.0019884   0.0285742   0.0023979   0.0097835   0.0245633   0.0047490
  0.0058769   0.0004606   0.0071315   0.0384184

MTB > regress c15 on 1 in c10;
```

MTB > plot c26 vs. c20



MTB > plot c29 vs. c26



MTB > correlation between c29 and c26

Correlation of pennscr and penres = 0.995

Figure 68 D.S. - left hand - pens residuals

```
MTB > regress c45 on 1 in c40;
SUBC> xlof;
SUBC> pure.

The regression equation is
log(hvc) = 3.13 - 0.00507 lhvcand

Predictor       Coef       Stdev    t-ratio       p
Constant      3.1289      0.1050      29.80   0.000
lhvcand   -0.0050715   0.0007179      -7.06   0.000

s = 0.2539      R-sq = 57.4%     R-sq(adj) = 56.3%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      3.2165      3.2165     49.91    0.000
Error         37      2.3846      0.0644
Total         38      5.6011

Unusual Observations
Obs. lhvcand  log(hvc)       Fit Stdev.Fit  Residual    St.Resid
 11       84    3.2958    2.7029    0.0546    0.5929       2.39R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.32  P = 0.2692  DF(pure error) = 27


MTB > print c48

hvccookd
  0.021695   0.100479   0.013911   0.000019   0.010178   0.185257   0.007380
  0.034012   0.022462   0.001916   0.138874   0.001612   0.017171   0.000005
  0.001821   0.000432   0.015392   0.039286   0.005926   0.034349   0.024111
  0.048846   0.008682   0.001071   0.018460   0.035955   0.004489   0.007397
  0.006335   0.002223   0.020576   0.024891   0.011636   0.002373   0.000923
  0.006086   0.051691   0.036064   0.082329

MTB > regress c35 on 1 in c30;
```

```
MTB > plot c46 vs. c40

         -
 hvcres  -             *
         -   *
         -                                  *
      1.5+                               *
         -                         *     *                         *
         -        *                                *               2
         - *
         -             *                             *
      0.0+   *                     *
         -             *           *  *     *      * *
         - * *    *                      *     3   * *
         -        *                         *      *
         -                            *     *
     -1.5+ *                                *
         -                            *
         -
          ---------+---------+---------+---------+---------+--------lhvcand
                  70       105       140       175       210
```

```
MTB > plot c49 vs. c46

 hvcnscr -
         -                                                       *
         -                                                  *
      1.5+                                               *
         -                                       *  *  *
         -                                     ***
         -                             *   * **
         -                       * 2   *
      0.0+                    **2*
         -                   4
         -                 22
         -               *2
         -           2*
     -1.5+        *
         -      *
         -   *
         -
           ----+---------+---------+---------+---------+---------+--hvcres
           -1.60     -0.80      0.00      0.80      1.60      2.40

MTB > correlation between c49 and c46

Correlation of hvcnscr and hvcres = 0.978
```

Figure 69 D.S. - left hand - heavier can residuals

```
SUBC> xlof;
SUBC> pure.

The regression equation is
log(ltc) = 2.56 - 0.00253 lltcand

Predictor        Coef        Stdev    t-ratio       p
Constant      2.56003      0.08089      31.65   0.000
lltcand    -0.0025256    0.0005589      -4.52   0.000

s = 0.1960      R-sq = 35.6%     R-sq(adj) = 33.8%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1     0.78457     0.78457     20.42    0.000
Error         37     1.42187     0.03843
Total         38     2.20644

Unusual Observations
Obs. lltcand  log(ltc)       Fit Stdev.Fit  Residual    St.Resid
 15      126    2.6672    2.2418    0.0317    0.4254       2.20R

R denotes an obs. with a large st. resid.
Lack of fit test
Possible curvature in variable lltcand (P = 0.016)
Overall lack of fit test is significant at P = 0.016

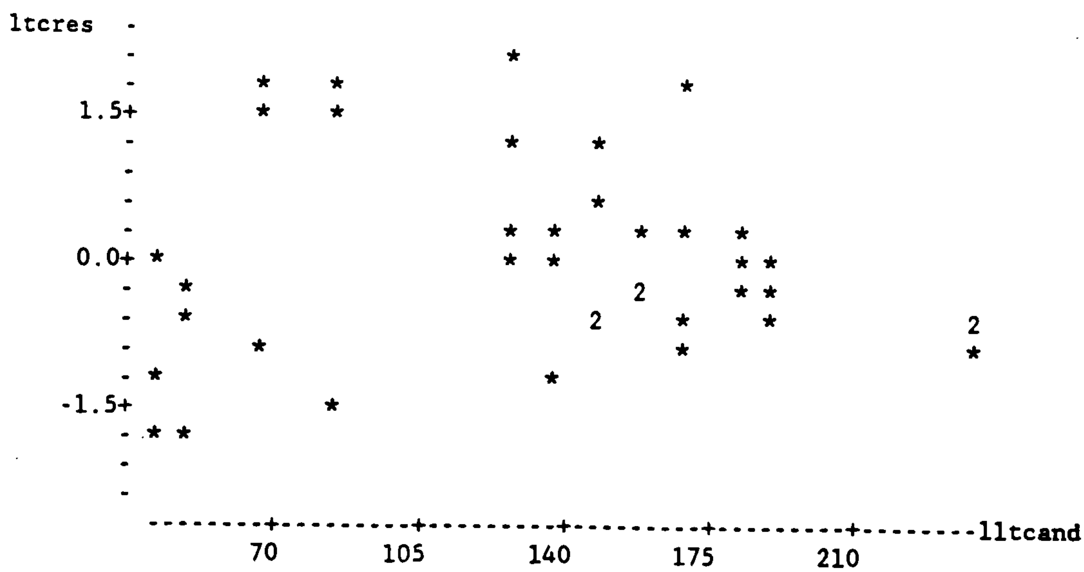
Pure error test - F = 1.57  P = 0.1696  DF(pure error) = 27


MTB > print c38

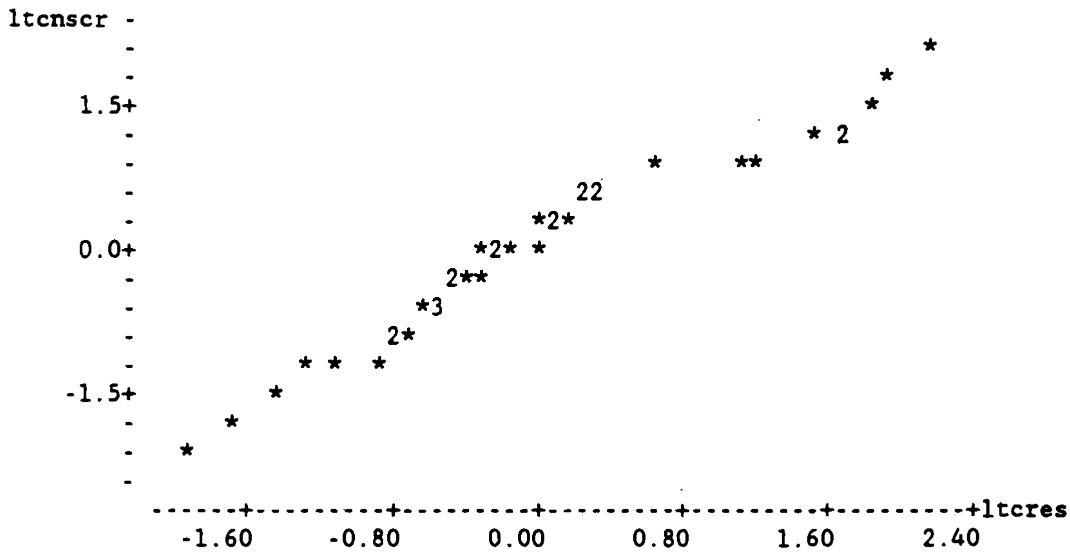
ltccookd
  0.001030   0.078355   0.140858   0.002207   0.170377   0.024480   0.091011
  0.022298   0.087243   0.084228   0.046788   0.055050   0.018323   0.000032
  0.064757   0.000921   0.001649   0.000090   0.015944   0.005717   0.005546
  0.017765   0.003505   0.000847   0.002022   0.000556   0.060322   0.005727
  0.010816   0.001253   0.000009   0.002535   0.003337   0.002342   0.008883
  0.000032   0.020044   0.014446   0.053173

MTB > regress c56 on 1 in c55;
```

MTB > plot c36 vs. c30



MTB > plot c39 vs. c36



MTB > correlation between c39 and c36

Correlation of ltcnscr and ltcres = 0.979

Figure 70 D.S. - left hand - lighter can residuals

```
SUBC> xlof;
SUBC> pure.

The regression equation is
15ballt = 18.0 - 0.0189 15balld

Predictor       Coef        Stdev    t-ratio        p
Constant      17.967        5.091       3.53    0.002
15balld     -0.01890      0.02775      -0.68    0.503

s = 4.562       R-sq = 2.1%      R-sq(adj) = 0.0%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1        9.66        9.66      0.46    0.503
Error         22      457.92       20.81
Total         23      467.58

Unusual Observations
Obs. 15balld   15ballt        Fit Stdev.Fit  Residual    St.Resid
  3      147    28.300     15.188     1.313    13.112       3.00R

R denotes an obs. with a large st. resid.
Lack of fit test
Possible curvature in variable 15balld (P = 0.073)
Overall lack of fit test is significant at P = 0.073

Pure error test - F = 1.74  P = 0.1797  DF(pure error) = 17

MTB > regress c71 on 1 in c70;
SUBC> xlof;
SUBC> pure.

The regression equation is
rpenst = 6.55 - 0.00724 rpensd

Predictor       Coef        Stdev    t-ratio        p
Constant      6.5483       0.3321      19.72    0.000
rpensd     -0.007242     0.002300      -3.15    0.003

s = 0.8041      R-sq = 21.6%     R-sq(adj) = 19.4%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      6.4091      6.4091      9.91    0.003
Error         36     23.2744      0.6465
Total         37     29.6834

Unusual Observations
Obs.  rpensd    rpenst        Fit Stdev.Fit  Residual    St.Resid
  2       43     9.000      6.237     0.244     2.763       3.61R

R denotes an obs. with a large st. resid.
```

```
Possible lack of fit at outer X-values      (P = 0.060)
Overall lack of fit test is significant at P = 0.060

Pure error test - F = 1.65  P = 0.1468  DF(pure error) = 26

MTB > regress c61 on 1 in c60;
SUBC> xlof;
SUBC> pure.

The regression equation is
rqdnpt = 7.42 - 0.0123 rqdnpd

Predictor        Coef        Stdev    t-ratio        p
Constant       7.4174       0.6308      11.76    0.000
rqdnpd      -0.012267     0.004356      -2.82    0.008

s = 1.522       R-sq = 18.5%     R-sq(adj) = 16.1%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      18.384      18.384      7.93    0.008
Error         35      81.119       2.318
Total         36      99.503

Unusual Observations
Obs.  rqdnpd     rqdnpt        Fit Stdev.Fit  Residual    St.Resid
  1       43     10.300      6.890     0.465     3.410       2.35R
 19      147     10.800      5.614     0.258     5.186       3.46R

R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.98  P = 0.0815  DF(pure error) = 25

MTB > regress c91 on 1 in c90;
```

```
SUBC> xlof;
SUBC> pure.

The regression equation is
rhvcant = 3.38 - 0.00518 rhvcand

Predictor        Coef        Stdev    t-ratio        p
Constant       3.3787       0.1745      19.36    0.000
rhvcand     -0.005175     0.001197      -4.32    0.000

s = 0.4225      R-sq = 34.8%     R-sq(adj) = 32.9%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      3.3355      3.3355     18.69    0.000
Error         35      6.2478      0.1785
Total         36      9.5832

Unusual Observations
Obs. rhvcand    rhvcant       Fit Stdev.Fit  Residual   St.Resid
  4       48     4.0000    3.1303    0.1240    0.8697      2.15R
 33      188     3.3000    2.4058    0.0951    0.8942      2.17R
 36      238     3.0000    2.1470    0.1428    0.8530      2.15R
R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.61  P = 0.1611  DF(pure error) = 25

MTB > regress c81 on  1 in c80;
SUBC> xlof;
SUBC> pure.

The regression equation is
rltcant = 4.01 - 0.00941 rltcand

Predictor        Coef        Stdev    t-ratio        p
Constant       4.0114       0.2871      13.97    0.000
rltcand     -0.009412     0.001987      -4.74    0.000

s = 0.6927      R-sq = 39.7%     R-sq(adj) = 38.0%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      10.764      10.764     22.43    0.000
Error         34      16.316       0.480
Total         35      27.080

Unusual Observations
Obs. rltcand    rltcant       Fit Stdev.Fit  Residual   St.Resid
  4       48      6.500     3.560     0.203     2.940      4.44R

R denotes an obs. with a large st. resid.
```

```
Possible lack of fit at outer X-values       (P = 0.000)
Overall lack of fit test is significant at P = 0.000

Pure error test - F = 2.71  P = 0.0222  DF(pure error) = 24

MTB > regress c51 on 1 in c50;
SUBC> xlof;
SUBC> pure.

The regression equation is
rplcrdt = 5.49 - 0.00899 rplcrdd

Predictor        Coef        Stdev     t-ratio        p
Constant       5.4883       0.3406       16.11    0.000
rplcrdd     -0.008985     0.002358       -3.81    0.001

s = 0.8219      R-sq = 29.9%     R-sq(adj) = 27.9%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      9.8112      9.8112     14.52    0.001
Error         34     22.9688      0.6756
Total         35     32.7800

Unusual Observations
Obs. rplcrdd   rplcrdt        Fit Stdev.Fit  Residual    St.Resid
  7       68     6.500      4.877     0.204     1.623       2.04R
 13      126     7.000      4.356     0.138     2.644       3.26R

R denotes an obs. with a large st. resid.

Lack of fit test
Possible curvature in variable rplcrdd (P = 0.000)
Overall lack of fit test is significant at P = 0.000

Pure error test - F = 2.73  P = 0.0214  DF(pure error) = 24
```

```
MTB > regress c97 on 1 in c96;
SUBC> xlof;
SUBC> pure.

The regression equation is
r5ballt = 6.60 - 0.0135 r5balld

Predictor        Coef        Stdev    t-ratio        p
Constant        6.599        1.150       5.74    0.000
r5balld     -0.013477     0.006939      -1.94    0.071

s = 0.4988      R-sq = 20.1%     R-sq(adj) = 14.8%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1      0.9386      0.9386      3.77    0.071
Error        15      3.7319      0.2488
Total        16      4.6706


No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.51  P = 0.2645  DF(pure error) = 11
```

```
MTB > regress c2 on 1 in c1;

SUBC> xlof;
SUBC> pure.

The regression equation is
rgrstrlb = 7.24 + 0.168 rgrstrd

Predictor        Coef       Stdev    t-ratio        p
Constant        7.240       1.352       5.35    0.000
rgrstrd       0.16817     0.01928       8.72    0.000

s = 5.911       R-sq = 56.3%     R-sq(adj) = 55.6%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      2659.3      2659.3     76.10    0.000
Error         59      2061.7        34.9
Total         60      4721.0

Unusual Observations
Obs. rgrstrd  rgrstrlb        Fit Stdev.Fit  Residual    St.Resid
 21       36    25.000     13.295     0.869    11.705       2.00R

R denotes an obs. with a large st. resid.
Lack of fit test
Possible curvature in variable rgrstrd (P = 0.000)
Overall lack of fit test is significant at P = 0.000

Pure error test - F = 4.99  P = 0.0000  DF(pure error) = 44

MTB > regress c11 on 1 in c10;
SUBC> xlof;
SUBC> pure.

The regression equation is
rlatstlb = 2.41 + 0.0374 rlatstrd

Predictor        Coef       Stdev    t-ratio        p
Constant       2.4051      0.4683       5.14    0.000
rlatstrd     0.037365    0.005432       6.88    0.000

s = 1.148       R-sq = 53.0%     R-sq(adj) = 51.9%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      62.396      62.396     47.31    0.000
Error         42      55.393       1.319
Total         43     117.790

Unusual Observations
Obs.rlatstrd  rlatstlb        Fit Stdev.Fit  Residual    St.Resid
 24       78     8.000      5.320     0.174     2.680       2.36R
 32      106     9.000      6.366     0.223     2.634       2.34R
```

```
R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.55  P = 0.1647  DF(pure error) = 31

MTB > regress c45 on 1 in c40;
SUBC> xlof;
SUBC> pure.

The regression equation is
log(pen) = 5.76 - 0.00823 r5pensd

Predictor        Coef        Stdev     t-ratio        p
Constant       5.7564       0.1524       37.78    0.000
r5pensd     -0.008235     0.001889       -4.36    0.000

s = 0.4050       R-sq = 32.2%      R-sq(adj) = 30.5%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      3.1174      3.1174     19.01    0.000
Error         40      6.5600      0.1640
Total         41      9.6774

Unusual Observations
Obs. r5pensd  log(pen)       Fit Stdev.Fit  Residual    St.Resid
 26       78    3.9416    5.1141    0.0630   -1.1725      -2.93R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.75  P = 0.1122  DF(pure error) = 29


MTB > print c47

pencookd
  0.000073   0.004027   0.030675   0.001010   0.015689   0.004805   0.015239
  0.008016   0.001478   0.053870   0.035685   0.022650   0.040532   0.003736
  0.051288   0.002556   0.024067   0.007123   0.000165   0.005145   0.026375
  0.002647   0.006298   0.000016   0.000001   0.106686   0.023274   0.000617
  0.000500   0.044544   0.009373   0.052578   0.022393   0.009465   0.056522
  0.004688   0.020617   0.035773   0.084511   0.006228   0.022826   0.003907

MTB > regress c55 on 1 in c50;
```

```
MTB > plot c46 vs. c40

          -                    *
       1.6+             *             *             *
          -             *                                  *      *
  penvar  -                                                *
          -       * *              2                   *
          -       * *          *      *                           2
       0.0+   *                    *     2          *
          -   *   *        *                        *      *
          -         *               *                *          *
          -   *            *                           *   *
          -                    *         *
      -1.6+                *                           *
          -
          -
          -
          -                              *
      -3.2+
            +---------+---------+---------+---------+---------+------r5pensd
           20        40        60        80       100       120
```

```
MTB > plot c48 vs. c46

 pennscr  -
          -                                                     *
          -                                                   *
       1.5+                                                  2
          -                                                 **
          -                                           **    *
          -                                         *22
          -                                       *3
       0.0+                                   *3 2
          -                                 **2
          -                              2***
          -                          ***
          -                        * *
      -1.5+                      **
          -                      *
          -      *
          -
            ----+---------+---------+---------+---------+---------+--penvar
             -3.0      -2.0      -1.0       0.0       1.0       2.0
```

```
MTB > correlation between c48 and c46

Correlation of pennscr and penvar = 0.987
```

Figure 71 C.R. - right hand - pens residuals

```
SUBC> xlof;
SUBC> pure.

The regression equation is
log(bal) = 4.08 - 0.00366 r5balld

Predictor        Coef        Stdev    t-ratio        p
Constant       4.0840       0.1436      28.44    0.000
r5balld     -0.003664     0.001805      -2.03    0.049

s = 0.4017      R-sq = 9.3%      R-sq(adj) = 7.1%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      0.6648      0.6648      4.12    0.049
Error         40      6.4535      0.1613
Total         41      7.1183

Unusual Observations
Obs. r5balld  log(bal)       Fit Stdev.Fit  Residual    St.Resid
 12       44    3.0155    3.9228    0.0797   -0.9073      -2.30R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

Pure error test - F = 3.06  P = 0.0085  DF(pure error) = 30


Correlation of ballnscr and ballres = 0.995

MTB > print c57

C57
  0.00666   0.00195   0.00126   1.00210   0.00187   0.01000   0.00788
  0.01032   0.01016   0.00272   0.00664   0.25970   0.00843   0.00243
  0.00293   0.00915   0.01898   0.12645   0.00529   0.00811   0.19474
  0.14764   0.00347   0.00914   0.00723   0.00243   0.00938   0.00992
  0.00592   0.00903   0.01106   0.00991   0.00690   0.03449   0.00831
  0.00702   0.00431   0.00138   0.16697   0.00515   0.01651   0.00042

MTB > regress c61 on 1 in c60;
```

```
MTB > plot c56 vs. c50

         -
         -       *            *      *
      1.5+                    *      *
         -
 ballres -       *     *             *            *
         -   *                                    *  *   *
         -         2                    *            *   *      *
      0.0+       *     *  *             *         *      *
         -         *          *         *                       2
         -                *                                     *
         -   2                                    *
         -             *  *                          *
     -1.5+                *                                     *
         -
         -                *
         -             *
         -
          +---------+---------+---------+---------+---------+---------+------r5balld
          20        40        60        80       100       120
```

```
MTB > plot c58 vs. c56

 ballnscr-
         -                                                         *
         -                                                        *
      1.5+                                                    *   *
         -                                              *    *
         -                                            2*
         -                                      *2 **
         -                                    *3
      0.0+                                 32*
         -                             3 *
         -                      * **  2
         -                    2*
         -                *  *
     -1.5+               **
         -        *
         -    *
         -
           --+---------+---------+---------+---------+---------+---------+----ballres
           -2.40     -1.60     -0.80     0.00      0.80      1.60

MTB > correlation between c58 and c56
```

Figure 72   C.R. - right hand - balls residuals

```
SUBC> xlof;
SUBC> pure.

The regression equation is
lgrpstlb = 76.1 + 0.103 lgrpstd

Predictor        Coef        Stdev     t-ratio       p
Constant       76.093        2.244       33.92   0.000
lgrpstd       0.10321      0.03105        3.32   0.002

s = 9.606       R-sq = 17.0%      R-sq(adj) = 15.5%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      1019.9      1019.9     11.05    0.002
Error         54      4983.1        92.3
Total         55      6003.0

Unusual Observations
Obs. lgrpstd  lgrpstlb        Fit Stdev.Fit  Residual   St.Resid
  3        0     52.80      76.09      2.24    -23.29     -2.49R
 38       78    106.00      84.14      1.41     21.86      2.30R

R denotes an obs. with a large st. resid.
Possible lack of fit at outer X-values      (P = 0.018)
Overall lack of fit test is significant at P = 0.018

Pure error test - F = 1.55  P = 0.1363  DF(pure error) = 39

MTB > regress c71 on 1 in c70;
SUBC> xlof;
SUBC> pure.

The regression equation is
llatplb = 14.3 + 0.0582 llatpd

Predictor        Coef        Stdev     t-ratio       p
Constant      14.2733       0.8410       16.97   0.000
llatpd        0.05822      0.01017        5.72   0.000

s = 2.057       R-sq = 46.3%      R-sq(adj) = 44.9%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      138.64      138.64     32.76    0.000
Error         38      160.80        4.23
Total         39      299.44

Unusual Observations
Obs.   llatpd    llatplb        Fit Stdev.Fit  Residual   St.Resid
 21        71     24.000     18.407     0.330     5.593      2.75R
 22        71     24.000     18.407     0.330     5.593      2.75R
```

```
R denotes an obs. with a large st. resid.

Lack of fit test
Possible curvature in variable llatpd (P = 0.000)
Overall lack of fit test is significant at P = 0.000

Pure error test - F = 7.33  P = 0.0000  DF(pure error) = 27

MTB > regress c76 on 1 in c75;
SUBC> xlof;
SUBC> pure.

The regression equation is
lpplb = 17.1 + 0.0269 lppd

Predictor        Coef       Stdev    t-ratio        p
Constant      17.0626      0.4262      40.04    0.000
lppd         0.026853    0.005113       5.25    0.000

s = 1.025        R-sq = 42.7%     R-sq(adj) = 41.2%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      28.984      28.984     27.59    0.000
Error         37      38.875       1.051
Total         38      67.859

Unusual Observations
Obs.     lppd      lpplb        Fit Stdev.Fit  Residual    St.Resid
 27       100     17.500     19.748     0.202    -2.248      -2.24R
 37       128     23.000     20.500     0.308     2.500       2.56R

R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 2.01  P = 0.0698  DF(pure error) = 26
```

```
MTB > regress c81 on 1 in c80;
SUBC> xlof;
SUBC> pure.

The regression equation is
15penst = 6.12 - 0.0105 15pensd

Predictor       Coef        Stdev     t-ratio        p
Constant      6.1191       0.2526       24.23    0.000
15pensd    -0.010499     0.003490       -3.01    0.004

s = 0.8553      R-sq = 17.1%     R-sq(adj) = 15.2%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      6.6199      6.6199      9.05    0.004
Error         44     32.1897      0.7316
Total         45     38.8096

Unusual Observations
Obs. 15pensd   15penst       Fit Stdev.Fit  Residual    St.Resid
  1        8     9.100     6.035     0.229     3.065       3.72R
 37      106     7.800     5.006     0.197     2.794       3.36R

R denotes an obs. with a large st. resid.
Possible lack of fit at outer X-values       (P = 0.000)
Overall lack of fit test is significant at P = 0.000

Pure error test - F = 2.69  P = 0.0118  DF(pure error) = 31

MTB > regress c91 on 1 in c90;
SUBC> xlof;
SUBC> pure.

The regression equation is
15ballt = 6.02 - 0.0161 15balld

Predictor       Coef        Stdev     t-ratio        p
Constant      6.0170       0.2756       21.83    0.000
15balld    -0.016126     0.003423       -4.71    0.000

s = 0.6735      R-sq = 40.2%     R-sq(adj) = 38.4%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      10.069      10.069     22.20    0.000
Error         33      14.970       0.454
Total         34      25.039

Unusual Observations
Obs. 15balld   15ballt       Fit Stdev.Fit  Residual    St.Resid
  4       31     6.900     5.517     0.184     1.383       2.13R

R denotes an obs. with a large st. resid.
```

```
MTB > regress c41 on 1 in c40;
SUBC> xlof;
SUBC> pure.

The regression equation is
rprstrlb = 13.8 + 0.0556 rgrpstrd

Predictor       Coef        Stdev    t-ratio        p
Constant      13.782        1.268      10.87    0.000
rgrpstrd     0.05561      0.01659       3.35    0.003

s = 2.500       R-sq = 37.2%     R-sq(adj) = 33.9%

Analysis of Variance

SOURCE        DF          SS          MS          F        p
Regression     1      70.241      70.241      11.24    0.003
Error         19     118.712       6.248
Total         20     188.952

Unusual Observations
Obs.rgrpstrd  rprstrlb       Fit Stdev.Fit  Residual    St.Resid
  2       22    20.000    15.005     0.951     4.995       2.16R
  5       40    11.000    16.006     0.727    -5.006      -2.09R

R denotes an obs. with a large st. resid.

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.38  P = 0.2872  DF(pure error) = 15

MTB > regress c51 on 1 in c50;
SUBC> xlof;
SUBC> pure.

The regression equation is
rlatstlb = 5.08 + 0.00715 rlatstrd

Predictor       Coef        Stdev    t-ratio        p
Constant      5.0835       0.5829       8.72    0.000
rlatstrd    0.007155     0.007467       0.96    0.350

s = 1.070       R-sq = 4.6%      R-sq(adj) = 0.0%

Analysis of Variance

SOURCE        DF          SS          MS          F        p
Regression     1       1.051       1.051       0.92    0.350
Error         19      21.758       1.145
Total         20      22.810

Unusual Observations
Obs.rlatstrd  rlatstlb       Fit Stdev.Fit  Residual    St.Resid
  5       40     7.500     5.370     0.332     2.130       2.09R
 17       98     8.000     5.785     0.306     2.215       2.16R
```

```
MTB > regress c61 on 1 in c60;
SUBC> xlof;
SUBC> pure.

The regression equation is
rppstrlb = 3.54 + 0.0136 rppstrd

Predictor        Coef       Stdev     t-ratio        p
Constant       3.5367      0.5627        6.29    0.000
rppstrd      0.013578    0.007226        1.88    0.077

s = 1.011       R-sq = 17.2%     R-sq(adj) = 12.3%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1       3.612       3.612      3.53    0.077
Error         17      17.388       1.023
Total         18      21.000

Unusual Observations
Obs. rppstrd  rppstrlb       Fit Stdev.Fit  Residual    St.Resid
  5       40     6.000     4.080     0.322     1.920       2.00R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.59  P = 0.2346  DF(pure error) = 13

MTB > regress c15 on 1 in c10;
SUBC> xlof;
SUBC> pure.

The regression equation is
log(pen) = 4.44 - 0.00942 rpensd

Predictor        Coef       Stdev     t-ratio        p
Constant       4.4406      0.1081       41.07    0.000
rpensd      -0.009421    0.001592       -5.92    0.000

s = 0.3286      R-sq = 58.3%     R-sq(adj) = 56.7%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      3.7790      3.7790     35.00    0.000
Error         25      2.6989      0.1080
Total         26      6.4780

Unusual Observations
Obs.  rpensd  log(pen)       Fit Stdev.Fit  Residual    St.Resid
 26        0    5.2679    4.4406    0.1081    0.8273       2.67R

R denotes an obs. with a large st. resid.
```

```
No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.70  P = 0.1748  DF(pure error) = 19

MTB > plot c16 vs. c10

         - *
 penres  -
         -
         -                                                         *
      1.5+
         - *
         -       *             *                                   *
         -                     *
         - *          *                2                 *         *
      0.0+                                                  2      *
         -                                               *
         -       *             *                            *
         - *                           *
         -                     *       *                 *
     -1.5+            *
         -            *
         -
           +---------+---------+---------+---------+---------+------rpensd
           0        20        40        60        80       100

MTB > plot c18 vs. c16

 pennscr -
         -                                                        *
         -
      1.5+                                            *
         -                                    **
         -                                  * *
         -                            2 *
         -                          2*
      0.0+                       * 2
         -                 * *   *
         -             * **
         -         * *
         -       **
     -1.5+  *
         -
         - *
         -
           --+---------+---------+---------+---------+---------+----penres
           -1.60     -0.80     0.00      0.80      1.60      2.40
```

Figure 73   M.E. - right hand - pens residuals

```
MTB > correlation between c18 and c16

Correlation of pennscr and penres = 0.985

MTB > print c17

pencook
  0.008707   0.035539   0.045176   0.011572   0.000791   0.091026   0.100757
  0.023408   0.008280   0.029274   0.006319   0.017192   0.002722   0.001122
  0.026017   0.002889   0.003453   0.056486   0.000036   0.011810   0.000638
  0.176435   0.049677   0.003658   0.000022   0.431638   0.075903

MTB > regress c35 on 1 in c30;
SUBC> xlof;
SUBC> pure.

The regression equation is
log(bal) = 3.42 - 0.00376 r5ballsd

Predictor        Coef       Stdev    t-ratio        p
Constant      3.42256     0.08888      38.51    0.000
r5ballsd    -0.003761    0.001129      -3.33    0.004

s = 0.1775      R-sq = 39.5%     R-sq(adj) = 35.9%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1     0.34919     0.34919     11.09    0.004
Error         17     0.53545     0.03150
Total         18     0.88464

Unusual Observations
Obs.r5ballsd  log(bal)       Fit Stdev.Fit  Residual    St.Resid
 17       112    3.3810   3.0013    0.0626    0.3796       2.29R

R denotes an obs. with a large st. resid.
```

```
MTB > plot c36 vs. c30

          -
  ballres -                                                       *
          -
          -
       1.5+                                             *
          -
          -          *        *                            *
          -
          -                   *       *                 *  *
       0.0+          *
          -                           *                    *
          -     2                                       *
          -                                                       *
          -                                                       *
      -1.5+                                                       *
          -                           *
          -
            --------+---------+---------+---------+---------+--------r5ballsd
                   20        40        60        80       100

MTB > plot c38 vs. c36

  ballnscr-                                                      *
          -
          -                                            *
       1.2+                                     *
          -                                     *
          -                                     *
          -                            2
          -                           2
       0.0+                        *
          -                    **
          -                   2
          -                   *
          -              *
      -1.2+           *
          -     *
          -
          -    *
            ----+---------+---------+---------+---------+---------+--ballres
            -1.60     -0.80     0.00      0.80      1.60      2.40
```

Figure 74   M.E. - right hand - balls residuals

```
MTB > correlation between c38 and c36

Correlation of ballnscr and ballres - 0.985

MTB > print c37

ballcook
  0.026049   0.028686   0.000693   0.077837   0.044574   0.001644   0.004389
  0.094187   0.001606   0.008220   0.001429   0.084640   0.045643   0.002196
  0.003737   0.183334   0.370715   0.058368   0.094763

MTB > regress c71 on 1 in c70;
SUBC> xlof;
SUBC> pure.

The regression equation is
lgrpstlb - 33.7 + 0.0516 lgrpstd

Predictor        Coef        Stdev    t-ratio        p
Constant       33.704        1.602      21.04    0.000
lgrpstd       0.05160      0.02458       2.10    0.046

s - 5.093        R-sq - 14.5%     R-sq(adj) - 11.2%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      114.33      114.33      4.41    0.046
Error         26      674.35       25.94
Total         27      788.68

Unusual Observations
Obs. lgrpstd  lgrpstlb       Fit Stdev.Fit  Residual    St.Resid
 19       91    28.000    38.400     1.356   -10.400      -2.12R

R denotes an obs. with a large st. resid.
No evidence of lack of fit (P > 0.1)

Pure error test - F - 1.41  P - 0.2596  DF(pure error) - 20
```

```
MTB > regress c76 on 1 in c75

The regression equation is
llatplb = 13.9 - 0.0185 llatpd

Predictor       Coef       Stdev    t-ratio       p
Constant     13.9105      0.6128      22.70   0.000
llatpd     -0.018515    0.007478      -2.48   0.022

s = 1.161        R-sq = 23.5%     R-sq(adj) = 19.6%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1       8.266       8.266      6.13    0.022
Error        20      26.972       1.349
Total        21      35.239


MTB > regress c81 on 1 in c80;
SUBC> xlof;
SUBC> pure.

The regression equation is
lppstlb = 13.2 - 0.00521 lppstd

Predictor       Coef       Stdev    t-ratio       p
Constant     13.1976      0.6606      19.98   0.000
lppstd     -0.005208    0.008740      -0.60   0.559

s = 1.236        R-sq = 2.0%      R-sq(adj) = 0.0%

Analysis of Variance

SOURCE       DF          SS          MS         F        p
Regression    1       0.543       0.543      0.36    0.559
Error        17      25.984       1.528
Total        18      26.526

Unusual Observations
Obs.  lppstd   lppstlb        Fit Stdev.Fit  Residual    St.Resid
  6       40    16.000     12.989     0.376     3.011       2.56R

R denotes an obs. with a large st. resid.
```

```
MTB > regress c86 on 1 in c85;
SUBC> xlof;
SUBC> pure.

The regression equation is
15penst = 9.38 - 0.0107 15pensd

Predictor        Coef        Stdev    t-ratio        p
Constant       9.3827       0.6482      14.47    0.000
15pensd     -0.010741     0.009517      -1.13    0.272

s = 1.855        R-sq = 5.7%      R-sq(adj) = 1.2%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1       4.385       4.385      1.27    0.272
Error         21      72.285       3.442
Total         22      76.670

Unusual Observations
Obs. 15pensd    15penst        Fit Stdev.Fit  Residual   St.Resid
  7       40     15.100      8.953     0.411     6.147      3.40R
 19      112     12.000      8.180     0.669     3.820      2.21R

MTB > regress c96 on 1 in c95;
SUBC> xlof;
SUBC> pure.

The regression equation is
15ballt = 13.5 - 0.0579 15balld

Predictor        Coef        Stdev    t-ratio        p
Constant       13.488        1.312      10.28    0.000
15balld      -0.05792      0.01648      -3.51    0.004

s = 2.093        R-sq = 48.7%     R-sq(adj) = 44.8%

Analysis of Variance

SOURCE        DF          SS          MS         F        p
Regression     1      54.106      54.106     12.35    0.004
Error         13      56.931       4.379
Total         14     111.037

Unusual Observations
Obs. 15balld    15ballt        Fit Stdev.Fit  Residual   St.Resid
  1       22     16.000     12.213     0.993     3.787      2.06R

R denotes an obs. with a large st. resid.
```

No evidence of lack of fit (P > 0.1)

Pure error test - F = 1.43 P = 0.3006 DF(pure error) = 9

MTB > regress c91 on 1 in c90

The regression equation is
lqdnpt = 11.9 - 0.0073 lqdnpd

Predictor	Coef	Stdev	t-ratio	p
Constant	11.9137	0.7529	15.82	0.000
lqdnpd	-0.00730	0.01158	-0.63	0.535

s = 2.435   R-sq = 1.7%   R-sq(adj) = 0.0%

Analysis of Variance

SOURCE	DF	SS	MS	F	p
Regression	1	2.353	2.353	0.40	0.535
Error	23	136.390	5.930		
Total	24	138.742			

Unusual Observations

Obs.	lqdnpd	lqdnpt	Fit	Stdev.Fit	Residual	St.Resid
4	11	6.600	11.833	0.661	-5.233	-2.23R
14	91	16.600	11.250	0.684	5.350	2.29R

APPENDIX C
Controller Specifics

```
LETT-PACKARD: 6809 Assembler                                       Tue Feb 13
E: /users/kamper/main
ATION OBJECT CODE LINE     SOURCE LINE

                       1 "6809"  XREF    LIST
           <5000>      2 STIM    EQU     5000H
           <3800>      3 PIADA   EQU     3800H
           <3801>      4 PIACA   EQU     3801H
           <3802>      5 PIADB   EQU     3802H
           <3803>      6 PIACB   EQU     3803H
           <0000>      7 ST1     EQU     0
           <0014>      8 ST2     EQU     20
           <0028>      9 ST3     EQU     40
           <003C>     10 ST4     EQU     60
           <0064>     11 PNTR1   EQU     100
           <0066>     12 PNTR2   EQU     102
           <0068>     13 PNTR3   EQU     104
           <006A>     14 PNTR4   EQU     106
           <006E>     15 EPT1    EQU     110
           <0070>     16 EPT2    EQU     112
           <0072>     17 EPT3    EQU     114
           <0074>     18 EPT4    EQU     116
           <0200>     19 FLAG    EQU     200H
           <0201>     20 BEGIN   EQU     201H
           <0202>     21 PWTOG1  EQU     202H
           <0203>     22 PWTOG2  EQU     203H
           <0204>     23 PWTOG3  EQU     204H
           <0205>     24 PWTOG4  EQU     205H
           <0206>     25 STOP    EQU     206H
           <0207>     26 STIM1   EQU     207H
           <0208>     27 CNT1    EQU     208H
           <0209>     28 CNT2    EQU     209H
           <020A>     29 CNT3    EQU     20AH
           <020B>     30 CNT4    EQU     20BH
           <020C>     31 DNPRG   EQU     20CH
           <020D>     32 MNYCH   EQU     20DH
           <020E>     33 NUMCH   EQU     20EH
                      34         GLB     STIM,PIACA,PIADA,PIACB,PIADB
                      35         GLB     ST1,ST2,ST3,ST4,PNTR1,PNTR2,PNTR3,PNTR
                      36         GLB     EPT1,EPT2,EPT3,EPT4,FLAG,BEGIN,STOP
                      37         GLB     PWTOG1,PWTOG2,PWTOG3,PWTOG4
                      38         GLB     STIM1,CNT1,CNT2,CNT3,CNT4,DNPRG,MNYCH,
                      39 ***************************** INITIALIZE FLAGS & STACKS
 0000 10CE 1FFF       40         LDS     #1FFFH
 0004 CE 12FF         41         LDU     #12FFH
 0007 1A 50           42         ORCC    #01010000B
 0009 7F 0207         43         CLR     STIM1
 000C 7F 5000         44         CLR     STIM
 000F 7F 0206         45         CLR     STOP
 0012 7F 0201         46         CLR     BEGIN
 0015 7F 0200         47         CLR     FLAG
 0018 7F 020C         48         CLR     DNPRG
 001B 7F 0202         49         CLR     PWTOG1
 001E 7F 0203         50         CLR     PWTOG2
 0021 7F 0204         51         CLR     PWTOG3
 0024 7F 0205         52         CLR     PWTOG4
                      53 *************************** INITIALIZE PIA ***********
 0027 86 20           54         LDA     #20H
 0029 B7 3801         55         STA     PIACA
 002C 5F              56         CLRB
 002D F7 3800         57         STB     PIADA
```

```
HEWLETT-PACKARD: 6809 Assembler                                          Tue Feb 18
FILE: /users/kamper/main
LOCATION OBJECT CODE LINE     SOURCE LINE

   0030 86 25          58           LDA     #25H
   0032 B7 3801        59           STA     PIACA
   0035 86 28          60           LDA     #28H
   0037 B7 3803        61           STA     PIACB
   003A C6 FF          62           LDB     #0FFH
   003C F7 3802        63           STB     PIADB
   003F 86 2C          64           LDA     #2CH
   0041 B7 3803        65           STA     PIACB
   0044 7F 3802        66           CLR     PIADB
   0047 1C EF          67           ANDCC   #11101111B
                       68 ************************ WAIT FOR INTERRUPTS *********
   0049 B6 020C        69 NYET      LDA     DNPRG
   004C 27 FB          70           BEQ     NYET
   004E 1C BF          71           ANDCC   #10111111B
   0050 12             72 THERE     NOP
   0051 20 FD          73           BRA     THERE
                       74           END

Errors=     0
```

CROSS REFERENCE TABLE Tue Feb 18 16:32:28 1992 PAGE
FILE: /users/kamper/main

LINE#	SYMBOL	TYPE	REFERENCES		
20	BEGIN	A	36,	46	
27	CNT1	A	38		
28	CNT2	A	38		
29	CNT3	A	38		
30	CNT4	A	38		
31	DNPRG	A	38,	48,	69
15	EPT1	A	36		
16	EPT2	A	36		
17	EPT3	A	36		
18	EPT4	A	36		
19	FLAG	A	36,	47	
32	MNYCH	A	38		
33	NUMCH	A	38		
69	NYET	P	70		
4	PIACA	A	34,	55,	59
6	PIACB	A	34,	61,	65
3	PIADA	A	34,	57	
5	PIADB	A	34,	63,	66
11	PNTR1	A	35		
12	PNTR2	A	35		
13	PNTR3	A	35		
14	PNTR4	A	35		
21	PWTOG1	A	37,	49	
22	PWTOG2	A	37,	50	
23	PWTOG3	A	37,	51	
24	PWTOG4	A	37,	52	
7	ST1	A	35		
8	ST2	A	35		
9	ST3	A	35		
10	ST4	A	35		
2	STIM	A	34,	44	
26	STIM1	A	38,	43	
25	STOP	A	36,	45	
72	THERE	P	73		

```
WLETT-PACKARD: 6809 Assembler                                    Mon Mar  2
LE: /users/kamper/prg
CATION OBJECT CODE LINE     SOURCE LINE

                          "6809"   XREF    LIST
           <020F>         ROW      EQU     20FH
           <0210>         COL      EQU     210H
           <0211>         KEY      EQU     211H
           <0212>         CHTOG    EQU     212H
           <0213>         CHAN     EQU     213H
           <0214>         CHFLG    EQU     214H
                                   EXT     PIACA,PIADA,PIACB,PIADB
                                   EXT     ST1,ST2,ST3,ST4,EPT1,EPT2,EPT3,EPT4
                                   EXT     PNTR1,PNTR2,PNTR3,PNTR4
                                   EXT     CNT1,CNT2,CNT3,CNT4
                                   EXT     FLAG,DNPRG,NUMCH,MNYCH
                          **************************** START ROUTINE *******
  0000 1A 50                       ORCC    #01010000B
  0002 BD 00DA                     JSR     SCAN
  0005 B6 0211                     LDA     KEY
  0008 81 10                       CMPA    #10H
  000A 27 30                       BEQ     NWPR
  000C 81 11                       CMPA    #11H
  000E 27 5E                       BEQ     SETFLG
  0010 81 12                       CMPA    #12H
  0012 27 71                       BEQ     NXTCH
  0014 81 13                       CMPA    #13H
  0016 1027 0099                   LBEQ    ENDPR
  001A F6 0214                     LDB     CHFLG
  001D 26 57                       BNE     TTLCH
  001F F6 0212                     LDB     CHTOG
  0022 27 7E                       BEQ     NEWCH
  0024 F6 0213                     LDB     CHAN
  0027 108E 0000                   LDY     #PNTR1
  002B A7 B5                       STA     [B,Y]
  002D EC A5                       LDD     B,Y
  002F C3 0001                     ADDD    #1
  0032 1F 01                       TFR     D,X
  0034 F6 0213                     LDB     CHAN
  0037 AF A5                       STX     B,Y
  0039 1C EF                       ANDCC   #11101111B
  003B 3B                          RTI
                          ****************************** NEW PROGRAM ************
  003C 7C 0000            NWPR     INC     FLAG
  003F 7F 0212                     CLR     CHTOG
  0042 8E 0000                     LDX     #ST1
  0045 86 50                       LDA     #80
  0047 6F 80              Z        CLR     ,X+
  0049 4A                          DECA
  004A 26 FB                       BNE     Z
  004C BD 0055                     JSR     POSPTR
  004F 1C EF                       ANDCC   #11101111B
  0051 BD 00D4                     JSR     STALL
  0054 3B                          RTI
                          ****************************** POSITION POINTERS******
  0055 8E 0000            POSPTR   LDX     #ST1
  0058 BF 0000                     STX     PNTR1
  005B 8E 0000                     LDX     #ST2
  005E BF 0000                     STX     PNTR2
  0061 8E 0000                     LDX     #ST3
  0064 BF 0000                     STX     PNTR3
```

```
:WLETT-PACKARD: 6809 Assembler                                    Mon Mar  2
:LE: /users/kamper/prg
)CATION OBJECT CODE LINE     SOURCE LINE

 0067 8E 0000                    LDX     #ST4
 006A BF 0000                    STX     PNTR4
 006D 39                         RTS
                       ****************************** SET CHANNEL FLAG ******
 006E C6 01              SETFLG  LDB     #1
 0070 F7 0214                    STB     CHFLG
 0073 1C EF                      ANDCC   #11101111B
 0075 3B                         RTI
                       ****************************** NUMBER OF CHANNELS ****
 0076 B6 0211            TTLCH   LDA     KEY
 0079 B7 0000                    STA     NUMCH
 007C B7 0000                    STA     MNYCH
 007F 7F 0214                    CLR     CHFLG
 0082 1C EF                      ANDCC   #11101111B
 0084 3B                         RTI
                       ****************************** NEXT CHANNEL **********
 0085 B6 0213            NXTCH   LDA     CHAN
 0088 108E 0000                  LDY     #PNTR1
 008C EC A6                      LDD     A,Y
 008E 108E 0000                  LDY     #EPT1
 0092 C3 0001                    ADDD    #1
 0095 1F 01                      TFR     D,X
 0097 B6 0213                    LDA     CHAN
 009A AF A6                      STX     A,Y
 009C 7F 0212                    CLR     CHTOG
 009F 1C EF                      ANDCC   #11101111B
 00A1 3B                         RTI
                       ***************************** NEW CHANNEL ************
 00A2 B6 0211            NEWCH   LDA     KEY
 00A5 80 01                      SUBA    #1
 00A7 C6 02                      LDB     #2
 00A9 3D                         MUL
 00AA F7 0213                    STB     CHAN
 00AD 7C 0212                    INC     CHTOG
 00B0 1C EF                      ANDCC   #11101111B
 00B2 3B                         RTI
                       **************************** END OF PROGRAMMING ******
 00B3 7F 0000            ENDPR   CLR     FLAG
 00B6 B6 0213                    LDA     CHAN
 00B9 108E 0000                  LDY     #PNTR1
 00BD EC A6                      LDD     A,Y
 00BF C3 0001                    ADDD    #1
 00C2 1F 01                      TFR     D,X
 00C4 108E 0000                  LDY     #EPT1
 00C8 B6 0213                    LDA     CHAN
 00CB AF A6                      STX     A,Y
 00CD BD 0055                    JSR     POSPTR
 00D0 7C 0000                    INC     DNPRG
 00D3 3B                         RTI
                       *************************** STALL - WAIT FOR NEXT KEY
 00D4 B6 0000            STALL   LDA     FLAG
 00D7 26 FB                      BNE     STALL
 00D9 39                         RTS
                       **************************** GET KEY *****************
 00DA 86 24              SCAN    LDA     #24H
 00DC B7 0000                    STA     PIACA
 00DF 86 FF                      LDA     #0FFH
```

```
EWLETT-PACKARD: 6809 Assembler                                   Mon Mar  2
ILE: /users/kamper/prg
OCATION OBJECT CODE LINE     SOURCE LINE

  00E1 B7 020F                   STA     ROW
  00E4 7F 0210                   CLR     COL
  00E7 C6 FE                     LDB     #11111110B
  00E9 F7 0000                   STB     PIADB
  00EC B6 0000          NXTROW   LDA     PIADA
  00EF 7C 020F          AGAIN    INC     ROW
  00F2 F6 020F                   LDB     ROW
  00F5 C1 04                     CMPB    #4
  00F7 27 47                     BEQ     NEXTCOL
  00F9 44                        LSRA
  00FA 25 F3                     BCS     AGAIN
  00FC BD 0134                   JSR     WAIT
  00FF F6 0210                   LDB     COL
  0102 C1 04                     CMPB    #4
  0104 27 11                     BEQ     SPECIAL
  0106 B6 020F                   LDA     ROW
  0109 C6 04                     LDB     #4
  010B 3D                        MUL
  010C 1E 89                     EXG     A,B
  010E BB 0210                   ADDA    COL
  0111 B7 0211                   STA     KEY
  0114 7E 011F                   JMP     RELEASE
                        *************** 5TH COLUMN *********************
  0117 86 10            SPECIAL  LDA     #10H
  0119 BB 020F                   ADDA    ROW
  011C B7 0211                   STA     KEY
                        *****************************************
  011F F6 0000          RELEASE  LDB     PIADA
  0122 C8 FF                     EORB    #11111111B
  0124 26 F9                     BNE     RELEASE
  0126 BD 0134                   JSR     WAIT
  0129 7F 0000          LEAVE    CLR     PIADB
  012C 86 25                     LDA     #25H
  012E B7 0000                   STA     PIACA
  0131 1C EF                     ANDCC   #11101111B
  0133 39                        RTS
  0134 86 80            WAIT     LDA     #80H
  0136 C6 FF            AG       LDB     #0FFH
  0138 12               LP       NOP
  0139 5A                        DECB
  013A 26 FC                     BNE     LP
  013C 4A                        DECA
  013D 26 F7                     BNE     AG
  013F 39                        RTS
  0140 F6 0210          NEXTCOL  LDB     COL
  0143 5C                        INCB
  0144 C1 05                     CMPB    #5
  0146 27 E1                     BEQ     LEAVE
  0148 F7 0210                   STB     COL
  014B C6 FF                     LDB     #0FFH
  014D F7 020F                   STB     ROW
  0150 79 0000                   ROL     PIADB
  0153 20 97                     BRA     NXTROW
                                 END

rrors=    0
```

CROSS REFERENCE TABLE Mon Mar 2 16:40:31 1992 PAGE
FILE: /users/kamper/prg

LINE#	SYMBOL	TYPE	REFERENCES
152	AG	P	157
120	AGAIN	P	125
6	CHAN	A	29, 35, 74, 80, 90, 96, 102
7	CHFLG	A	25, 63, 70
5	CHTOG	A	27, 41, 82, 91
11	CNT1	E	
11	CNT2	E	
11	CNT3	E	
11	CNT4	E	
3	COL	A	116, 127, 134, 159, 163
12	DNPRG	E	105
95	ENDPR	P	24
9	EPT1	E	77, 101
9	EPT2	E	
9	EPT3	E	
9	EPT4	E	
12	FLAG	E	40, 95, 108
4	KEY	A	16, 67, 86, 135, 140
146	LEAVE	P	162
153	LP	P	155
12	MNYCH	E	69
86	NEWCH	P	28
159	NEXTCOL	P	123
12	NUMCH	E	68
40	NWPR	P	18
74	NXTCH	P	22
119	NXTROW	P	167
8	PIACA	E	113, 148
8	PIACB	E	
8	PIADA	E	119, 142
8	PIADB	E	118, 146, 166
10	PNTR1	E	30, 53, 75, 97
10	PNTR2	E	55
10	PNTR3	E	57
10	PNTR4	E	59
52	POSPTR	P	47, 104
142	RELEASE	P	136, 144
2	ROW	A	115, 120, 121, 130, 139, 165
112	SCAN	P	15
62	SETFLG	P	20
138	SPECIAL	P	129
9	ST1	E	42, 52
9	ST2	E	54
9	ST3	E	56
9	ST4	E	58
108	STALL	P	49, 109
67	TTLCH	P	26
151	WAIT	P	126, 145
44	Z	P	46

```
EWLETT-PACKARD: 6809 Assembler                                   Thu Apr  9
ILE: /users/kamper/counter
OCATION OBJECT CODE LINE     SOURCE LINE

                          "6809"   XREF    LIST
                                   EXT     PNTR1,PNTR2,PNTR3,PNTR4,ST1,ST2,ST3,ST
                                   EXT     PWTOG1,PWTOG2,PWTOG3,PWTOG4
                                   EXT     EPT1,EPT2,EPT3,EPT4,BEGIN,MNYCH,NUMCH
                                   EXT     STIM,STIM1,CNT1,CNT2,CNT3,CNT4
                          ************************* START ROUTINE *************
  0000 B6 0000                     LDA     BEGIN
  0003 1027 0109                   LBEQ    NOBEG
  0007 7A 0000                     DEC     CNT1
  000A B6 0000                     LDA     CNT1
  000D 2F 02                       BLE     NXT1
  000F 20 37                       BRA     TWO
                          ************************ MOVE CH 1 POINTER **********
  0011 FC 0000            NXT1     LDD     PNTR1
  0014 C3 0001                     ADDD    #1
  0017 FD 0000                     STD     PNTR1
  001A 10B3 0000                   CMPD    EPT1
  001E 1027 00EF                   LBEQ    STOVR
  0022 10BE 0000                   LDY     PNTR1
  0026 A6 A4                       LDA     0,Y
  0028 B7 0000                     STA     CNT1
  002B B6 0000                     LDA     PWTOG1
  002E 27 0D                       BEQ     ON1
                          ************************ TURN OFF CH 1 ****************
  0030 7F 0000                     CLR     PWTOG1
  0033 86 FE                       LDA     #11111110B
  0035 B4 0000                     ANDA    STIM1
  0038 B7 0000                     STA     STIM1
  003B 20 0B                       BRA     TWO
                          ************************ TURN ON CH 1 *****************
  003D 7C 0000            ON1      INC     PWTOG1
  0040 86 01                       LDA     #1
  0042 BA 0000                     ORA     STIM1
  0045 B7 0000                     STA     STIM1
                          ********************** CHANNEL 2 *********************
  0048 7A 0000            TWO      DEC     NUMCH
  004B 102F 00B5                   LBLE    LEAVE
  004F 7A 0000                     DEC     CNT2
  0052 B6 0000                     LDA     CNT2
  0055 2F 02                       BLE     NXT2
  0057 20 2F                       BRA     THREE
  0059 FC 0000            NXT2     LDD     PNTR2
  005C C3 0001                     ADDD    #1
  005F FD 0000                     STD     PNTR2
  0062 10BE 0000                   LDY     PNTR2
  0066 A6 A4                       LDA     0,Y
  0068 B7 0000                     STA     CNT2
  006B B6 0000                     LDA     PWTOG2
  006E 27 0D                       BEQ     ON2
                          ************************* TURN OFF CH 2 *************
  0070 7F 0000                     CLR     PWTOG2
  0073 86 FD                       LDA     #11111101B
  0075 B4 0000                     ANDA    STIM1
  0078 B7 0000                     STA     STIM1
  007B 20 0B                       BRA     THREE
                          ************************* TURN ON CH 2 **************
  007D 7C 0000            ON2      INC     PWTOG2
```

```
EWLETT-PACKARD: 6809 Assembler                                   Thu Apr  9
ILE: /users/kamper/counter
OCATION OBJECT CODE LINE     SOURCE LINE

  0080 86 02                       LDA     #2
  0082 BA 0000                     ORA     STIM1
  0085 B7 0000                     STA     STIM1
                            ************************ CHANNEL 3 ******************
  0088 7A 0000              THREE  DEC     NUMCH
  008B 2F 77                       BLE     LEAVE
  008D 7A 0000                     DEC     CNT3
  0090 B6 0000                     LDA     CNT3
  0093 2F 02                       BLE     NXT3
  0095 20 2F                       BRA     FOUR
  0097 FC 0000              NXT3   LDD     PNTR3
  009A C3 0001                     ADDD    #1
  009D FD 0000                     STD     PNTR3
  00A0 10BE 0000                   LDY     PNTR3
  00A4 A6 A4                       LDA     0,Y
  00A6 B7 0000                     STA     CNT3
  00A9 B6 0000                     LDA     PWTOG3
  00AC 27 0D                       BEQ     ON3
                            ************************ TURN OFF CH 3 ***************
  00AE 7F 0000                     CLR     PWTOG3
  00B1 86 FB                       LDA     #11111011B
  00B3 B4 0000                     ANDA    STIM1
  00B6 B7 0000                     STA     STIM1
  00B9 20 0B                       BRA     FOUR
                            ************************ TURN ON CH 3 ****************
  00BB 7C 0000              ON3    INC     PWTOG3
  00BE 86 04                       LDA     #4
  00C0 BA 0000                     ORA     STIM1
  00C3 B7 0000                     STA     STIM1
                            ************************ CHANNEL 4 *******************
  00C6 7A 0000              FOUR   DEC     NUMCH
  00C9 2F 39                       BLE     LEAVE
  00CB 7A 0000                     DEC     CNT4
  00CE B6 0000                     LDA     CNT4
  00D1 2F 02                       BLE     NXT4
  00D3 20 2F                       BRA     LEAVE
  00D5 FC 0000              NXT4   LDD     PNTR4
  00D8 C3 0001                     ADDD    #1
  00DB FD 0000                     STD     PNTR4
  00DE 10BE 0000                   LDY     PNTR4
  00E2 A6 A4                       LDA     0,Y
  00E4 B7 0000                     STA     CNT4
  00E7 B6 0000                     LDA     PWTOG4
  00EA 27 0D                       BEQ     ON4
                            *********************** TURN OFF CH 4 ****************
  00EC 7F 0000                     CLR     PWTOG4
  00EF 86 F7                       LDA     #11110111B
  00F1 B4 0000                     ANDA    STIM1
  00F4 B7 0000                     STA     STIM1
  00F7 20 0B                       BRA     LEAVE
                            *********************** TURN ON CH 4 *****************
  00F9 7C 0000              ON4    INC     PWTOG4
  00FC 86 08                       LDA     #8
  00FE BA 0000                     ORA     STIM1
  0101 B7 0000                     STA     STIM1
  0104 B6 0000              LEAVE  LDA     STIM1
  0107 B7 0000                     STA     STIM
```

```
HEWLETT-PACKARD: 6809 Assembler                                    Thu Apr  9
FILE: /users/kamper/counter
LOCATION OBJECT CODE LINE     SOURCE LINE

    010A B6 0000        115           LDA      MNYCH
    010D B7 0000        116           STA      NUMCH
    0110 3B             117 NOBEG     RTI
                        118 ********************* REPEAT SEQUENCE ****************
    0111 7F 0000        119 STOVR     CLR      STIM1
    0114 7F 0000        120           CLR      STIM
    0117 8E 0000        121           LDX      #ST1             * RESET POINTERS AND C
    011A BF 0000        122           STX      PNTR1
    011D A6 84          123           LDA      0,X
    011F B7 0000        124           STA      CNT1
    0122 8E 0000        125           LDX      #ST2
    0125 BF 0000        126           STX      PNTR2
    0128 A6 84          127           LDA      0,X
    012A B7 0000        128           STA      CNT2
    012D 8E 0000        129           LDX      #ST3
    0130 BF 0000        130           STX      PNTR3
    0133 A6 84          131           LDA      0,X
    0135 B7 0000        132           STA      CNT3
    0138 8E 0000        133           LDX      #ST4
    013B BF 0000        134           STX      PNTR4
    013E A6 84          135           LDA      0,X
    0140 B7 0000        136           STA      CNT4
    0143 7F 0000        137           CLR      PWTOG1
    0146 7F 0000        138           CLR      PWTOG2
    0149 7F 0000        139           CLR      PWTOG3
    014C 7F 0000        140           CLR      PWTOG4
    014F 3B             141           RTI
                        142
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CROSS REFERENCE TABLE          Thu Apr  9 18:22:45 1992                    PAGE
FILE: /users/kamper/counter
LINE#   SYMBOL          TYPE     REFERENCES

    4  BEGIN             E      7
    5  CNT1              E      9,  10,  21, 124
    5  CNT2              E     38,  39,  47, 128
    5  CNT3              E     64,  65,  73, 132
    5  CNT4              E     90,  91,  99, 136
    4  EPT1              E     17
    4  EPT2              E
    4  EPT3              E
    4  EPT4              E
   88  FOUR              P     67,  81
  113  LEAVE             P     37,  63,  89,  93, 107
    4  MNYCH             E    115
  117  NOBEG             P      8
    4  NUMCH             E     36,  62,  88, 116
   14  NXT1              P     11
   42  NXT2              P     40
   68  NXT3              P     66
   94  NXT4              P     92
   31  ON1               P     23
   57  ON2               P     49
   83  ON3               P     75
  109  ON4               P    101
    2  PNTR1             E     14,  16,  19, 122
    2  PNTR2             E     42,  44,  45, 126
    2  PNTR3             E     68,  70,  71, 130
    2  PNTR4             E     94,  96,  97, 134
    3  PWTOG1            E     22,  25,  31, 137
    3  PWTOG2            E     48,  51,  57, 138
    3  PWTOG3            E     74,  77,  83, 139
    3  PWTOG4            E    100, 103, 109, 140
    2  ST1               E    121
    2  ST2               E    125
    2  ST3               E    129
    2  ST4               E    133
    5  STIM              E    114, 120
    5  STIM1             E     27,  28,  33,  34,  53,  54,  59,  60,  79,  80,  8
  119  STOVR             P     18
   62  THREE             P     41,  55
   36  TWO               P     12,  29
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HEWLETT-PACKARD: 6809 Assembler                                       Wed Dec  4
FILE: /users/kamper/stst
LOCATION OBJECT CODE LINE     SOURCE LINE

                       1 "6809"  XREF     LIST
                       2         EXT      BEGIN,STIM,STOP,STIM1
                       3         EXT      CNT1,CNT2,CNT3,CNT4
                       4         EXT      PNTR1,PNTR2,PNTR3,PNTR4,ST1,ST2,ST3,ST
                       5 *************************** START ROUTINE ************
  0000 B6 0000         6         LDA      STOP
  0003 26 30           7         BNE      STP
                       8 *************************** BEGIN STIMULATION ********
  0005 108E 0000       9         LDY      #ST1
  0009 A6 A4          10         LDA      0,Y
  000B B7 0000        11         STA      CNT1
  000E 108E 0000      12         LDY      #ST2
  0012 A6 A4          13         LDA      0,Y
  0014 B7 0000        14         STA      CNT2
  0017 108E 0000      15         LDY      #ST3
  001B A6 A4          16         LDA      0,Y
  001D B7 0000        17         STA      CNT3
  0020 108E 0000      18         LDY      #ST4
  0024 A6 A4          19         LDA      0,Y
  0026 B7 0000        20         STA      CNT4
  0029 7C 0000        21         INC      STOP
  002C BD 005F        22         JSR      DEBNCE
  002F 7C 0000        23         INC      BEGIN
  0032 1C BF          24         ANDCC    #10111111B
  0034 3B             25 NOBEG   RTI
                      26 ************************** STOP STIMULATION **********
  0035 7F 0000        27 STP     CLR      STIM
  0038 7F 0000        28         CLR      STIM1
  003B 7F 0000        29         CLR      BEGIN
  003E 7F 0000        30         CLR      STOP
  0041 8E 0000        31         LDX      #ST1              * RESET POINTERS
  0044 BF 0000        32         STX      PNTR1
  0047 8E 0000        33         LDX      #ST2
  004A BF 0000        34         STX      PNTR2
  004D 8E 0000        35         LDX      #ST3
  0050 BF 0000        36         STX      PNTR3
  0053 8E 0000        37         LDX      #ST4
  0056 BF 0000        38         STX      PNTR4
  0059 BD 005F        39         JSR      DEBNCE
  005C 1C BF          40         ANDCC    #10111111B
  005E 3B             41         RTI
  005F 86 D0          42 DEBNCE  LDA      #0D0H
  0061 C6 FF          43 AG      LDB      #0FFH
  0063 12             44 LP      NOP
  0064 5A             45         DECB
  0065 26 FC          46         BNE      LP
  0067 4A             47         DECA
  0068 26 F7          48         BNE      AG
  006A 39             49         RTS
                      50         END

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CROSS REFERENCE TABLE          Wed Dec  4 11:36:46 1991                    PAGE
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    3   CNT2              E      14
    3   CNT3              E      17
    3   CNT4              E      20
   42   DEBNCE            P      22,   39
   44   LP                P      46
   25   NOBEG             P
    4   PNTR1             E      32
    4   PNTR2             E      34
    4   PNTR3             E      36
    4   PNTR4             E      38
    4   ST1               E       9,   31
    4   ST2               E      12,   33
    4   ST3               E      15,   35
    4   ST4               E      18,   37
    2   STIM              E      27
    2   STIM1             E      28
    2   STOP              E       6,   21,   30
   27   STP               P       7
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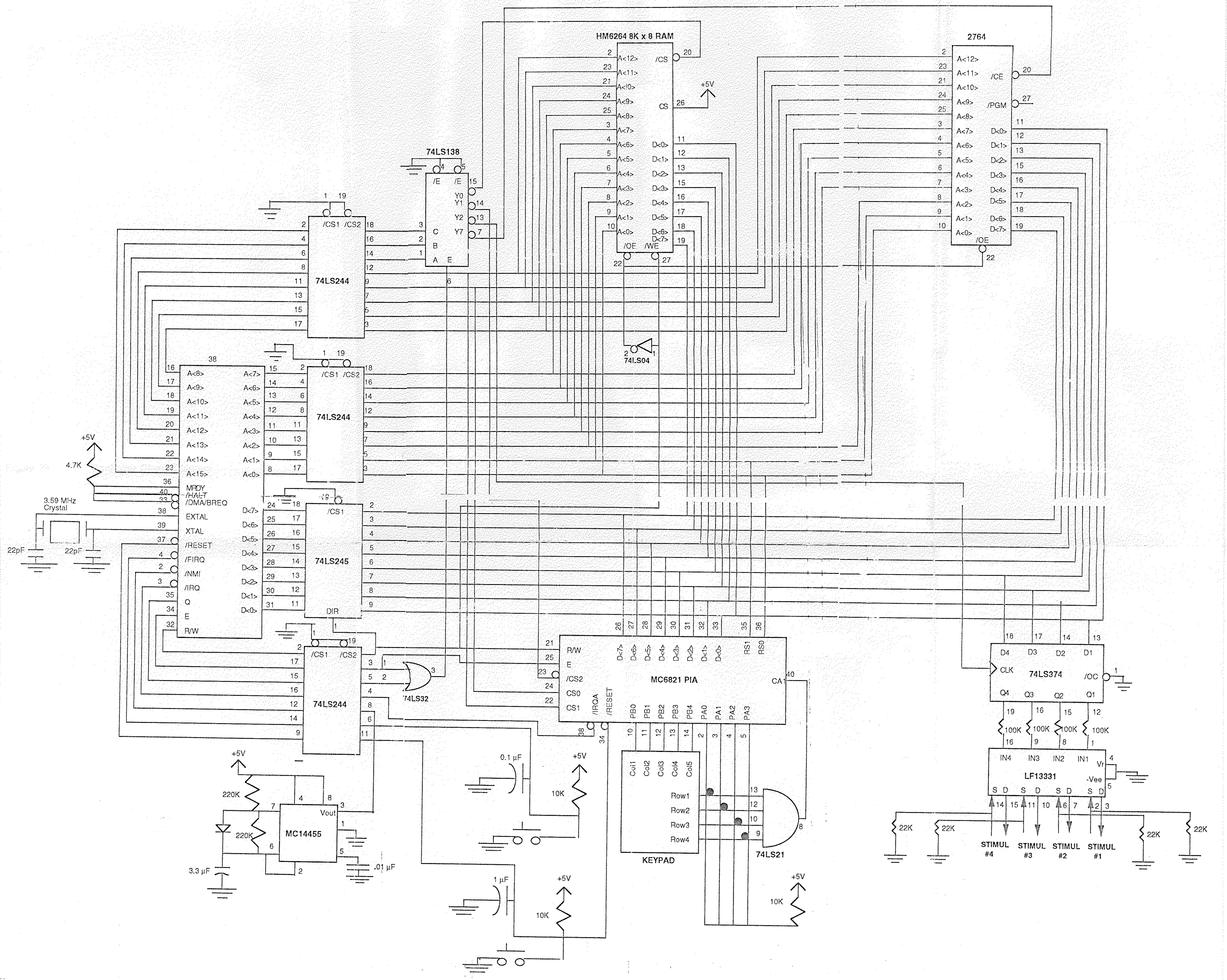
HM6264 8K x 8 RAM
2764
74LS138
74LS244
74LS244
74LS245
74LS244
74LS04
74LS32
MC6821 PIA
74LS374
LF13331
MC14455
74LS21
KEYPAD
3.59 MHz
Crystal
22pF
22pF
4.7K
+5V
220K
220K
3.3 µF
.01 µF
0.1 µF
1 µF
10K
10K
10K
100K
22K
STIMUL #4
STIMUL #3
STIMUL #2
STIMUL #1
MRDY
/HALT
/DMA/BREQ
EXTAL
XTAL
/RESET
/FIRQ
/NMI
/IRQ
Q
E
R/W
/CS
CS
/CE
/PGM
/OE
/WE
DIR
CA1
RS1
RS0
/IRQA
CLK
/OC
Vout
Vr
-Vee
Col1
Col2
Col3
Col4
Col5
Row1
Row2
Row3
Row4

Parts List

Part Number	Quantity	Price/Unit
MC6809	1	$4.15
MC6821	1	$1.73
HM6264	1	$4.49
2764A-25	1	$3.25
LF13331	1	$4.50
MC14455	1	$0.58
74LS244	3	$0.68
74LS245	1	$0.79
74LS138	1	$0.55
74LS374	1	$0.68
74LS32	1	$0.43
74LS21	1	$0.43
74LS04	1	$0.43
keypad	1	$7.59
3.59 MHz crystal	1	$1.79
socket-to-socket connector	1	$3.00
male 20-pin header	1	$2.75
40-pin socket	2	$3.17
28-pin socket	2	$2.30
20-pin socket	5	$1.98
16-pin socket	2	$1.25
14-pin socket	6	$1.01
8-pin socket	2	$0.84
	Total Cost:	$70.26

+5V Power supply not included

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