ADVANCES IN EXTERNAL CONTROL OF HUMAN EXTREMITIES IX

CONTROL OF THE FREELY-SWINGING PARALYZED LEG BEFORE AND AFTER EXERCISE

McNeal D.R., Nakai R.J., Meadows P. and Tu W.

Rancho Rehabilitation Engineering Center
Downey, California 90242 USA

ABSTRACT

An experimental model has been used to study issues that are relevant to the use of electrical stimulation to help paralyzed individuals walk. Modulated stimulation sequences for the quadriceps muscle were manually selected using an iterative trial-and-error procedure to cause the knee angle to follow a specific movement pattern (desired trajectory). Four paraplegic subjects were tested before and after an 8-week program in which the quadriceps was exercised daily with electrical stimulation. It was found that 12.6 ±2.9 iterations were required to approximate the desired trajectory. Upon completion of the iterative procedure, the Average Error between the actual and desired trajectories was 2.1° ±0.7. Repeated responses were extremely consistent; the Average Difference between repeated runs was less than 1° in 81% of the trials. When the stimulation sequence was repeated every 3 s for 50 cycles, there was a substantial progressive degradation in the response, even in exercised legs, that demonstrated the limitations of open-loop control. KEYWORDS: Electrical stimulation, quadriceps, open-loop control, exercise.

INTRODUCTION

Many research groups throughout the world are investigating the use of multichannel electrical stimulation of paralyzed muscles to assist neurologically impaired individuals during walking. In general, control is open-loop and stimulation sequences are preselected by a trial-and-error procedure in which stimulus intensities and timing are manually adjusted to achieve satisfactory performance. The study described in this paper addressed some basic issues relevant to such uses of stimulation; namely 1) the selection of stimulation sequences by a human operator to achieve a desired limb movement, 2) the consistency of repeated movements, and 3) the effects of muscle fatigue on achieving and maintaining the desired movement.

These issues are difficult, if not impossible, to study in walking subjects. The walking aids used by paralyzed subjects for support enable them to compensate for muscle fatigue and inconsistent responses to stimulation, thereby obscuring these effects and complicating their measurement. For this reason, a simplified model was chosen so these issues could be investigated under carefully controlled experimental conditions. In this study, subjects were seated and the only movement allowed was swinging of the lower leg at the knee. The movement to be achieved required activation of only the quadriceps muscle group (muscles that extend the knee). The quadriceps was chosen because of its importance in walking and because it could easily be stimulated with cutaneous electrodes.

METHODS

Subjects

Four paraplegic subjects, three males and one female, having complete lesions of the spinal cord resulting from traumatic injuries participated in this study. Their ages ranged from 20 to 38 years at the start of the study. The functional levels of their lesions ranged from T7 to T12, and the times post-injury ranged from 1 to 10 years.

Exercise Program

All four subjects participated in an 8-week conditioning program in their own homes in which the quadriceps of one leg (experimental leg) was exercised daily with electrical stimulation for up to two hours. Exercise was continued after the 8 weeks until all experimental tests were completed. The opposite leg (control leg) was not exercised.

Subjects exercised in their wheelchairs using cutaneous electrodes and a portable programmable UltraStim stimulator. Exercise was dynamic, beginning with the knee at approximately 60° of flexion and ending with extension to approximately 20°. A foam rubber leg and foot pad provided the 60° positioning and protected the foot and ankle joint. Full knee extension was avoided to minimize stresses on the impaired musculoskeletal tissues about the knee.

Testing for Strength and Endurance

Tests were conducted before, during and after the 8-week exercise program to document changes in muscle strength and endurance. Muscle testing was performed isometrically with the subject seated and the hip and knee in approximately 60° of flexion. Muscle "strength" was estimated by measuring the twitch response of the quadriceps muscle at a stimulus amplitude of 110 ma and a pulse duration of 0.3 ms. The endurance test consisted of 50 cycles of stimulation with a 1 s ON, 1 s OFF duty cycle. Stimulus amplitude was selected to generate 25-35% of the average moment at 110 ma. This lower moment was used for tetanic contractions to prevent damage to possibly osteoporotic bone.

Control of the Freely-Swinging Leg

Before and after the exercise period, studies were performed to document our ability to select control sequences to achieve predetermined movements (trajectories) of the lower leg. During these studies, subjects were seated in a test chair in an upright position. The buttocks and the leg not being tested were supported as usual during sitting, but the test leg was positioned so that the hip and the knee were in approximately 45° of flexion at rest. The position of the upper part of the test leg was fixed, but the lower leg was free to swing at the knee. The rest position determined the zero knee angle with extension from rest defined as positive. Knee angle was transduced by an electrogoniometer fabricated in our laboratory.

Biphasic regulated-current pulses were generated at 30 pulses/second (pps) and 0.3 ms pulsewidth by a dual Z80-based stimulator [3]. Amplitude modulation was used to regulate the level of muscle activation. Bipolar skin electrodes (4x9 cm, Axelgaard Manufacturing Co., Ltd., Huntington Beach, CA) were positioned over the quadriceps muscle to obtain a good motor response, and these locations were maintained in all subsequent test sessions.

The modulation envelope for the stimulus pulses was "drawn" with a Houston Instrument digitizing pad and displayed on a Modgraph graphics terminal. The operator had three options available for altering the control: the envelope could be shifted in time to alter the phasing of the control, the envelope could be multiplied by a selectable gain factor, or any portion of the envelope could be redrawn.

Knee angle was plotted on a Gould strip-chart recorder for instantaneous display and sampled at 30 Hz in synchrony with the stimulating pulses. The digitized data was stored in a Digital Equipment Corporation MINC LSI 11/23 computer and could be displayed on the graphics terminal following each run.

In each test session, one of the objectives was to determine a stimulation sequence for the quadriceps that would cause the knee angle to track a specific movement pattern (referred to as the desired trajectory). The desired trajectory used in this study was one in which the lower leg had to extend from the rest position to 30°, return to the rest position within 2 s, and remain at the rest position for the duration of the 3 s interval. Because the movement was slower than the frequency of the freely-swinging leg, only quadriceps activation was required to achieve the desired trajectory. The iterative procedure used to achieve a match between the actual trajectory and the desired trajectory is described in Results, but the goal in each case was to minimize the difference between the trajectories over the entire 3 s interval.

When a match was achieved, the final stimulation sequence was repeated to document the consistency of repeated responses and the effects of muscle fatigue. First, the stimulation sequence was repeated five times at 1-min intervals. One extended run was then made in which the sequence was repeated 50 times every 3 s. During this run the leg was manually stopped just prior to the end of each cycle so that the leg would start each cycle from the rest position.

To quantitate the quality of the match between the desired and actual trajectories, the following function, called the Average Error (AE), was defined:

$$\text{Average Error (AE)} = \frac{1}{q-p} \sum_{n=p}^{q} |A(nT) - D(nT)|$$

where A(nT) and D(nT) were the values (in degrees) of the actual and desired trajectories at time nT, and T was the interpulse interval

(33.3 ms). Parameters p and q were selected to cover the time interval over which movement occurs. For the desired trajectory shown in Fig. 4 this interval extended from 0.1 to 2.1 s (i.e., p=3 and q=63).

A second quantitative measure, called the Average Difference (AD), was defined as follows:

$$\text{Average Difference (AD)} = \frac{1}{q-p} \sum_{n=p}^{q} |A_i(nT) - A_{i+1}(nT)|$$

where $A_i(nT)$ and $A_{i+1}(nT)$ were the values at time nT of the actual trajectory on two successive repetitions of a stimulation sequence. AD was a measure of the variability in repeated responses, and it was computed over the same time interval as AE.

RESULTS

Effects of Exercise

The raw endurance data shown in Fig. 1 are from subject DM at Week 8. Prior to exercise, his endurance curves for the experimental and control legs superimposed. As seen in the figure, the normalized moments for both legs matched for approximately 20 cycles then diverged, which was commonly observed during the latter part of the program with all subjects.

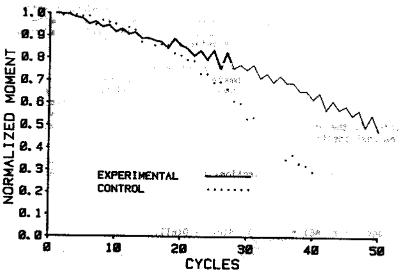

Figure 1. Endurance test. Data from subject DM at week 8.

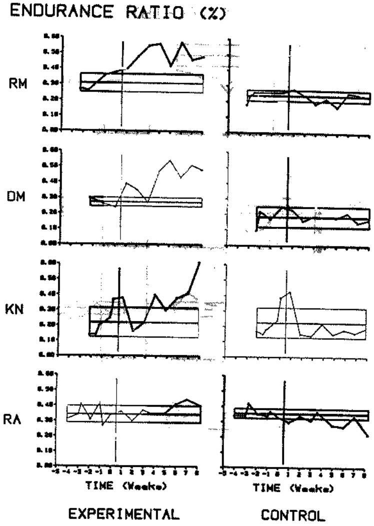

Figure 2. Endurance ratio values. Vertical lines mark beginning of exercise program. Solid horizontal lines and open bars represent means and standard deviations of the pre-exercise data.

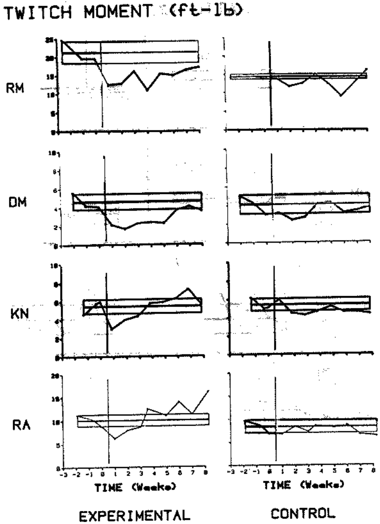

Figure 3. Twitch moment values at a stimulus amplitude of 110 mA. Vertical lines mark beginning of exercise program. Solid horizontal lines and open bars represent means and standard deviations of the pre-exercise data.

Fig. 2 shows the endurance ratio (moment at cycle 50 to maximum moment) plotted against weeks of exercise for both legs of all subjects. The pre-exercise means and standard deviations (SD) are illustrated for each leg by the horizontal lines and open bars. Improvements in the endurance parameters became noticeable following 1 to 4 weeks of exercise in 3 subjects. To compare the endurance ratio values at Week 8 with the pre-exercise values, the parameter improvements were compared to the pre-exercise SD values. At Week 8, th endurance ratio values improved by 3.0, 7.5, and 4.1 SD's above the pre-exercise mean values for the experimental legs of RM, DM, and KN, respectively. The endurance ratio for the experimental leg of subject RA demonstrated negligible improvement (1.1 SD). The endurance ratios of the control legs of all subjects demonstrated no improvement and ended within or below the standard deviation bars.

The changes in twitch moments, at 110 mA, with exercise are shown in Fig. 3. The moments of the experimental legs all decreased following one week of exercise by 3.0 to 3.2 SD's or 41 to 55% of the pre-exercise mean values for all subjects. During the next seven weeks, these moments slowly increased. For only two subjects, RA and KN, did this moment increase to above their pre-exercise mean values. No significant trends were observed in the moments for the control legs.

Selection of Control Sequences

The results of one iterative procedure are shown in Fig. 4. This session was conducted after completion of the conditioning program using the experimental leg of subject KN. In this case, 14 iterations were required to achieve a match, and iterations 3, 6, 11 and 14 are shown in the figure. The strategy used to program stimulation was to work first on the initial part of the trajectory and then, when that part was matched, continue to match subsequent portions of the trajectory, working from left to right. Once a part of the trajectory was matched, no attempt was made to go back and "touch-up" the stimulation sequence, even when there was degradation of the match on later iterations (e.g., note the fall-off in the rising phase of the response from Figs. 4b to 4d). In practice sessions in which this was attempted, the final match was not significantly improved and the number of iterations required was substantially increased.

No attempt was made to use data from previous sessions to shorten the iterative procedure (though the two persons conducting the study undoubtedly benefitted from those experiences), and no specific criteria were used to terminate the procedure. Each of the two operators were simply instructed to match the trajectory as best they could and to stop when they felt they could do no better.

The 14 iterations required to achieve an acceptable match in the case shown in Fig. 4 was slightly greater than the average of 12.6 ±2.9 iterations required in all 28 sessions. The minimum number of iterations required was 8 and the maximum was 18. There was no significant difference in the number of required iterations between the experimental and control legs, the conditioned and unconditioned legs, or the two operators who conducted these experiments. The time between iterations was generally about 2.5 min so the entire procedure took approximately one-half hour.

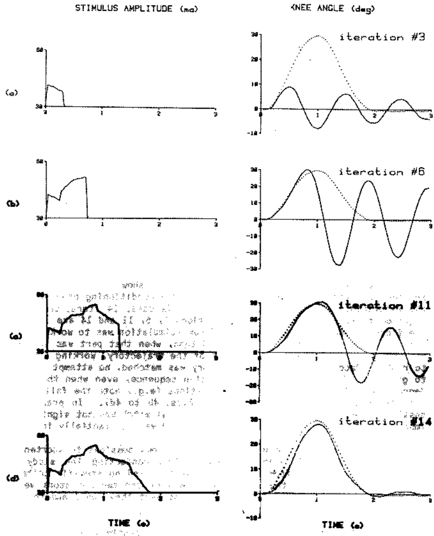

Figure 4. The desired trajectory (dotted line) is matched by trial-and-error selection of the modulated stimulation sequence to the quadriceps muscle. Stimulation sequences and the actual responses (solid line) for iterations 3, 6, 11 and 14 are shown. The strategy used to select sequences is described in the text.

TABLE I. Average Error on Final Iteration

	Mean	Standard Deviation	N
All Legs	2.1°	0.7°	28
Group 1. Experimental Legs, Before Conditioning	2.0°	0.6°	9
Group 2. Experimental Legs, After Conditioning	2.2°	0.7°	9
Group 3. Control Legs	2.0°	0.9°	10

The quality of the match achieved in Fig. 4 was typical of the results attained in general. The Average Error (AE) on the 14th iteration was 2.1°, which was equal to the mean AE on the final iteration of all sessions (Table I). Means and standard deviations of AE were also calculated for each of the three groups of legs. No significant difference was found between the groups; i.e., exercise had no apparent effect on the accuracy of the achieved match.

The most consistent problem encountered during these iterative procedures was a small but progressive degradation in the responses which was probably due to muscle fatigue. This effect can be seen in Fig. 4. On the 6th iteration (Fig. 4b), the rising phase of the trajectory was well-matched or slightly above the desired trajectory. By the 11th iteration (Fig. 4c), the actual trajectory had fallen below the desired trajectory, and on the 14th iteration (Fig. 4d), there was further degradation of the rising phase as well as degradation of the peak.

A second problem which was encountered in two of the subjects (DM and RA) was aberrant or unexpected responses. These responses usually occurred near the peak of the trajectory (i.e., during the period of greatest muscular activity), and were generally larger-than-expected responses. Aberrant responses occurred on a few iterations in about 50% of the sessions with DM and RA. While they extended the time required to achieve a match, the quality of the match finally achieved, as measured by AE, was not substantially different than that achieved in sessions in which these problems were not encountered.

Repeated Trials

Except for the few occurrences cited above, repeated responses were very consistent. The sequence shown in Fig. 4d was repeated five times at 1-min intervals, and the responses are shown superimposed in Fig. 5. In this case, the Average Differences (AD) between the 1st and 2nd, 2nd and 3rd, 3rd and 4th, and 4th and 5th repetitions were all equal to 0.4°. This value was slightly less than the mean AD of 0.7° on repeated trials in all

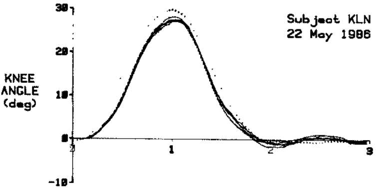

Figure 5. Superimposed responses from five trials in which the final stimulation sequence (Fig. 4d) was repeated at 1-minute intervals.

experimental sessions (Table II). For all repeated trials separated by a 1-min rest, the AD was less than 1° 81% of the time. No significant difference was seen between conditioned and unconditioned legs.

Even though repeated responses were very consistent there was generally an observable progressive degradation in the responses that accumulated over several trials. Even in the five traces shown in Fig. 5, the AE increases steadily from 2.1° on the first trial to 2.8° on the fifth trial. This degradation was usually in the direction of a diminished response to stimulation, an indication that the muscle was fatiguing despite the 1-min rest period between trials.

TABLE II. Average Difference on Repeated Trials

		Mean	Range	N
All Legs		0.7°	0.2-2.6°	100
Group 1.	Experimental Legs, Before Conditioning	0.8°	0.2-2.6°	26
Group 2.	Experimental Legs, After Conditioning	0.6°	0.3-1.6°	36
Group 3.	Control Legs	0.8°	0.3-2.5°	38

When the stimulation sequence was repeated every 3 s for 50 cycles, the decline in response became even more apparent as shown in Fig. 6. AE for cycles 1, 7, 19 and 50 were 2.9°, 3.7°, 5.6° and 7.8° respectively. These results were typical of all subjects as shown in Fig. 7. In this figure, means and standard deviations of the change in AE during the 50-cycle run were plotted for all subjects. Data for the conditioned legs and the unconditioned legs were plotted separately. After 15 cycles, there was an obvious separation between the two curves that became statistically significant by the 20th cycle ($P \geq 0.95$). By the 50th cycle the mean of the increase in AE was 7.3° for the unconditioned legs and 4.1° for the

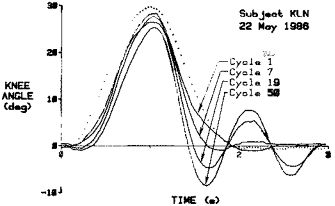

Figure 6. Cycles 1, 7, 19 and 50 of a 50-cycle run (period = 3 s) using the final stimulation sequence from Fig. 4d.

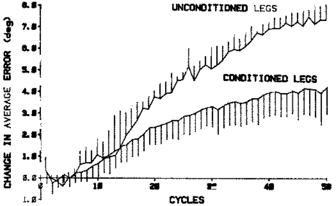

Figure 7. Means and standard deviations of the change in Average Error (see text for definition) during the 50-cycle run for conditioned and unconditioned legs.

conditioned legs. The mean AE at the beginning of the 50-cycle run (1st cycle) was 2.1° ±0.7 and 4.0° ±1.6 respectively for the unconditioned and conditioned legs.

While the degradation in response after 50 cycles was quite dramatic, the mean change in AE per cycle was less than 0.2° even during the first 20 cycles when the changes were greatest. This was comparable with the degradation observed in repeated trials with a 1-min rest interval. In other words, even though fatigue was more obvious during the 50-cycle run (compare Figs. 5 and 6), the degradation in response per cycle was essentially the same with or without a 1-min rest between trials.

DISCUSSION

Programming System

The iterative procedure and the programming system used to match the desired trajectory worked well: the system was easy to use, a match could be achieved within 20-45 minutes, and the mean AE between the actual and desired trajectories was 2.1° ±0.7. The time required to achieve a match could easily be reduced by 50% by switching to a faster graphics system since much time was lost waiting for instructions and data to appear on the screen.

Consistency of Repeated Responses

In general, repeated responses were extremely consistent, with the AD on repeated runs less than 1° about 80% of the time. These results are in sharp contrast to those reported by Trnkoczy [6]. He found repeated electrically-induced isometric contractions to be so inconsistent that he concluded that closed-loop control could not adequately compensate for the variability. Trnkoczy used hemiplegic subjects and studied the response of the ankle dorsiflexor muscles with the ankle constrained. The differences between subjects and experimental procedure in his study and ours could account for the discrepancy in results.

In a few cases during the present study, the AD was quite large; in one instance as high as 8.2°. While these erratic responses did not occur often, they could be a major problem in walking subjects. It is likely that these aberrations were reflexive responses triggered by electrical stimulation, though no attempt was made to document this in the present study. Further investigations of these phenomena should be conducted because of the potential danger of unexpected aberrant responses during electrically-assisted walking.

Electrically-induced Muscle Fatigue

The limiting factor in achieving a match of the desired trajectory in these experiments was fatigue. Even though the variability on successive trials was small, there was a progressive degradation in the responses that could accumulate over several trials to cause substantial errors. For this reason, the operator would ultimately reach a point where additional iterations to "touch up" one part of the trajectory were self-defeating; the additional iterations required would simply result in further degradation of the overall trajectory.

The observed degradation became more obvious when responses were repeated every 3 seconds (Figs. 6 and 7). Even in conditioned legs, the response began to degrade after the first few cycles and the degradation continued throughout the run. This clearly demonstrated the limitations of open-loop control and the need to eventually close the loop to achieve consistent walking patterns.

The amount of degradation was reduced with exercise (Fig. 7). This was expected based on previous reports that chronic electrically-induced exercise of muscle paralyzed by spinal-cord-injury (SCI) resulted in increased resistance to fatigue [1,5]. The mechanism for this change has not been documented in persons with SCI, but there is ample evidence from animal studies to suggest that it is due in part to a conversion of muscle fiber types from fibers that are easily fatigued to fibers that are fatigue-resistant [2,4].

ACKNOWLEDGEMENT

This research was supported by a grant from the National Science Foundation (ECS-8314643). Support for development of the programming system and the preliminary studies was provided by the National Institute of Disabilities and Rehabilitation Research (G008300077).

REFERENCES

[1] A. Kralj, T. Bajd and R. Turk, "Electrical stimulation providing functional use of paraplegic patient muscles," Med. Progr. Technol., vol. 7, pp. 3-9, 1980.

[2] R.L. Lieber, "Skeletal muscle adaptability. III. Muscle properties following chronic electrical stimulation," Dev. Med. Child Neurol., vol. 28, pp. 662-670, 1986.

[3] P. M. Meadows and D. R. McNeal, "A system for selection of modulated control sequences for functional electrical stimulation: II. A system hardware description," Proc. 2nd Int. Conf. Rehabil. Eng., pp. 527-528, 1984.

[4] J. T. Mortimer, "Motor prostheses," in Handbook of Physiology: The Nervous System I., J. M. Brookhart and V. B. Mountcastle, eds. Maryland: Am. Physiol. Soc., 1981, pp. 155-187.

[5] P. H. Peckham, J. T. Mortimer and E. B. Marsolais, "Alteration in the force and fatigability of skeletal muscle in quadriplegic humans following exercise induced by chronic electrical stimulation," Clin. Orthop., vol. 114, pp. 326-334, 1976.

[6] A. Trnkoczy, "Variability of electrically evoked muscle contractions with special regard to closed-loop controlled orthosis," Ann. Biomed. Eng., vol. 2, pp. 226, 1974.