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Sequential motor unit stimulation through peripheral motor nerves in the cat

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Abstract—*An electrode array is described that can be used to stimulate skeletal muscle through the peripheral motor nerves. This electrode array differs from the sleeve electrode that is used conventionally in that the motor units are stimulated sequentially, a mode of stimulation which closely mimics the normal asynchronous firing pattern of motor units that occurs during voluntary activity. Using this stimulation technique, tetanic contractions can be developed by muscle at low stimulation voltages and within physiological stimulation frequencies. Furthermore, unlike synchronous electrical stimulation, during sequential stimulation, submaximal tensions can be maintained for sustained periods of time. The applications of this electrode array to rehabilitation medicine are discussed*

Keywords—*Muscle fatigue, Rehabilitation, Strength*

1 Introduction

THE tension developed by skeletal muscle during low-frequency (<30 Hz) synchronous electrical stimulation can be characterised as a series of partially fused twitches. However, when the motor neurons innervating a skeletal muscle are divided into two or more equally sized bundles, which are then stimulated out of phase with one another (sequential stimulation), the muscle is able to develop tension smoothly at stimulation frequencies as low as 10 Hz (RACK and WESTBURY, 1969; PETROFSKY *et al.*, 1976; PETROFSKY, 1977). To develop a tension smoothly during synchronous stimulation requires frequencies of stimulation as high as 100 Hz (ECCLES and SHERRINGTON, 1930); stimulation frequencies that may lead to neuromuscular blockade (BROWN and BURNS, 1949). By using sequential stimulation, however, it is possible to tetanise muscle at stimulation frequencies less than 50 Hz (PETROFSKY *et al.*, 1976), and, by following a pattern of recruitment and firing frequency based on that recorded during voluntary isometric contractions, it is possible to maintain any submaximal tension smoothly for periods of time similar to those found in man during voluntary fatiguing isometric contractions (PETROFSKY, 1978).

Following spinal injuries, although the α motor neurons and their associated muscle fibres are still intact, the patient may be totally paralysed below the level of the injury. It can, therefore, be anticipated that sequential electrical stimulation of these motor neurons could be used to restore some degree of mobility to these individuals. Unfortunately, the method of separating these motor units into discrete bundles typically involves a complete dorsal laminectomy, a procedure far too radical to be easily used in corrective surgery for paralysed patients. PECKAM (1976) tried inserting three electrodes directly into skeletal muscle to simplify this procedure, but reported a variety of problems associated with electrode motion and maintaining a viable electrode contact. In addition, the same motor unit may receive stimuli from more than one electrode due to overlapping stimulation fields, causing the muscle to fatigue rapidly (PETROFSKY, 1977).

In the present investigation a sleeve electrode was developed that can stimulate a motor nerve in three discrete populations of motor units. Then, by sequential stimulation, it has been possible to develop and maintain smooth muscle contractions. These results are compared to those obtained after surgical division of the spinal nerves following a laminectomy since, here, complete isolation of motor unit populations is assured. These experiments were conducted during isometric contractions of the medial gastrocnemius muscle of the cat. This muscle was selected since its fibre composition is similar to that of most muscles in man (CLOSE, 1972; DUBOWITZ and BROOKE, 1973).

2 Methods

2.1 *Surgical preparation*

Female mongrel cats weighing between 1·9 and 3·8 kg were used in these experiments. The cats

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were initially anaesthetised with α chloralose given intraperitoneally at a dosage of 75 mg/kg and then maintained under anaesthesia by booster doses given through a jugular canula. Blood pressure was monitored throughout the experiments through a carotid canula.

Following this initial canulation, the animals were placed in the prone position on the surgical table; one of their rear legs was fixed to the table by 2 sets of steel clamps that were positioned onto the knee and lower leg bones. The skin from just above the T_1 to the S_3 segments of the spinal cord was then excised and a dorsal laminectomy was performed to expose the L_6, L_7, and S_1 ventral roots. These roots were then cut centrally, pooled together, and then redivided into 3 populations of ventral roots such that stimulation of each bundle in turn would elicit a similar isometric tension in the medial gastrocnemius muscle upon stimulation. These ventral root bundles were then continuously superfused with oxygenated liquid paraffin kept at a temperature of 38°C to keep the nerves viable and to ensure electrical isolation between the ventral root bundles.

A second incision was also made through the skin from the spinal cord to just over calcaneus to expose the medial head of gastrocnemius and the sciatic nerve. Medial gastrocnemius was freed of all connective tissue from its origin to insertion on calcaneus. All other tendons to calcaneus were then cut as well as the attachment of calcaneus to the lower leg bone. A pin, driven through calcaneus, was used to secure it to a low displacement tension transducer. A sleeve electrode (see Section 2.2) was placed on the sciatic nerve halfway between the spinal cord and the medial gastrocnemius muscle. Both the muscle and the sciatic nerve were superfused with oxygenated liquid paraffin which was warmed to a temperature of 38°C.

2.2 *Stimulation*

The medial gastrocnemius was stimulated indirectly either through the spinal cord or through the sleeve electrode.

To stimulate the muscle through the spinal cord, three pairs of electrodes were placed around the three populations of motor units whose separation was described under 'surgical preparations'. These populations of motor units were then stimulated sequentially by square-waves stimulii of 0·1 ms duration at frequencies between 10 and 100 Hz. Both stimulation frequency and pulse amplitude were controlled by a microprocessor controlled stimulator (Fig. 1), which has been described in

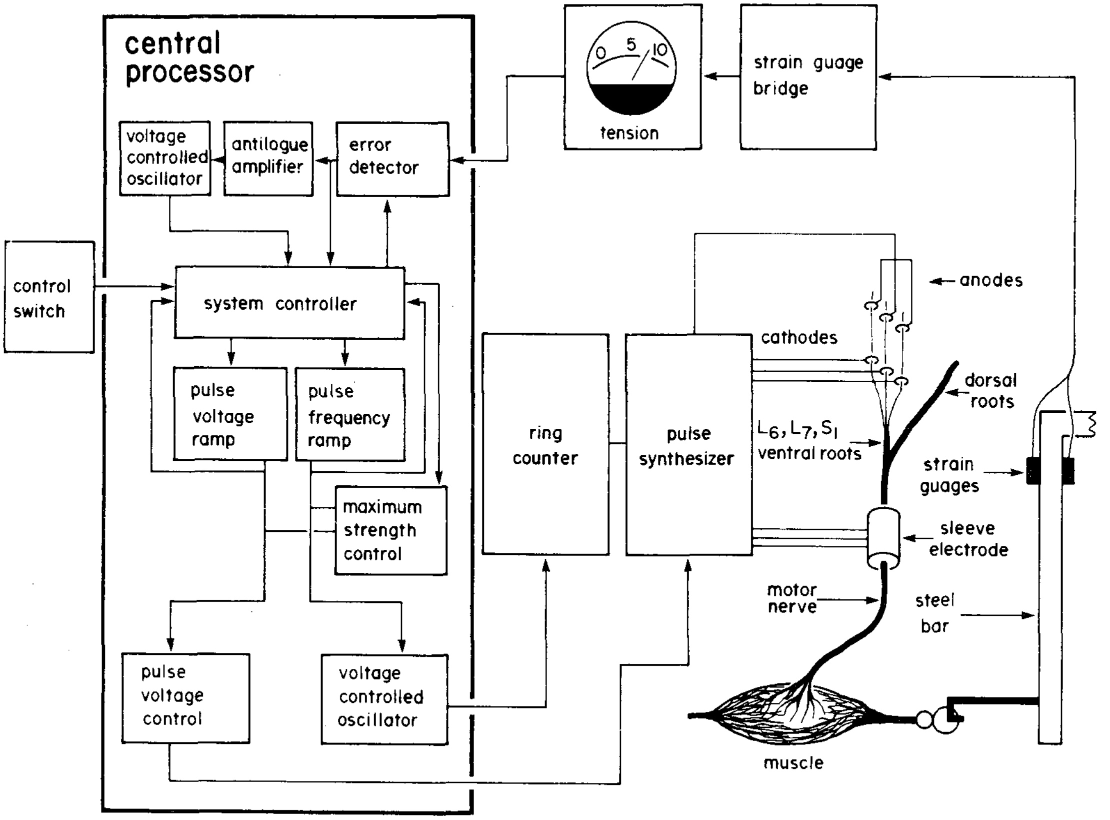

Fig. 1 Schematic of microprocessor-controlled sitmulation system used

detail in a previous publication (PETROFSKY, 1977), but in these experiments was based around the Intel 8080A microprocessor.

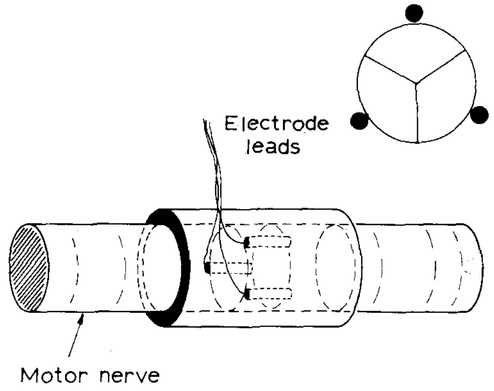

Fig. 2 Sleeve electrode used to stimulate sciatic nerve

Where stimulation was applied through the sciatic nerve, a sleeve electrode was used as shown in Fig. 2, consisting of three platinum electrodes encased in a polyurethane sheath. A longitudinal slit allowed the sheath to be opened to facilitate its placement around the sciatic nerve. Sequential stimulation was applied by alternately selecting one electrode as the active electrode and then connecting the remaining two together as the reference. Stimulation voltage was adjusted to 'recruit' differing numbers of motor neurons under the active electrode. The intention, then, was to divide the sciatic nerve electronically into three populations of motor neurons as shown on the top of this Figure. The stimuli were square waves with a pulse width of 0·1 ms and whose frequencies ranged from 10 to 100 Hz depending on the experimental circumstances.

2.3 *Recording of motor unit activity*

During sciatic nerve stimulation, motor unit activity was monitored through bipolar e.m.g. needle electrodes placed in the proximal end of medial gastrocnemius and positioned to record from single muscle fibres. The extracellular action potentials recorded in this manner were amplified through a d.c. amplifier (input impedence $10^8\ \Omega$) and displayed on a memory oscilloscope for analysis. The frequency response of the entire system was flat from d.c. to 4 kHz.

2.4 *Recording of electrical gradients in the nerve*

In one of the experiments described, it was necessary to measure the electrical gradient that was developed in the nerve during sequential stimulation. This was accomplished by making two of the three electrodes reference electrodes and applying a sinewave to the third at an amplitude of 1 V peak–peak and a frequency of 2 kHz; a frequency at which the axons are inexcitable. By using high frequency stimulation, the potential gradient could be measured by an extracellularly placed KCl-filled glass electrode inserted into the sciatic nerve, this measurement being independent of tissue excitability.

3 Procedures

Three series of experiments were conducted as described below.

Series 1: In the first series of experiments, the ability of the electrode array to subdivide the sciatic nerve was assessed. This was accomplished by applying a 1 V sinewave stimulus at a frequency of 2 kHz through one of the three sciatic electrodes; the remaining two electrodes were used as the reference. A glass recording microelectrode filled with concentrated KCl was then inserted into the nerve trunk at various depths through one of a series of holes in the sleeve electrode. From these measurements on four cats, the shape of the voltage field within the motor nerve during stimulation was determined.

Series 2: Once the properties of the sleeve electrode were established, the ability of the muscle to develop smooth isometric contractions at differing tensions was assessed. Muscle stimulation by the microprocessor was set to generate various tensions between 10 and 100% of the muscle's tetanic strength. The recruitment and firing frequency pattern used by the microprocessor to accomplish this end was based on the patterns of recruitment and firing frequency found during voluntary isometric activity in both cat (OLSEN *et al.*, 1968) and human muscle (MILNER–BROWN and STEIN, 1975; BIGLAND and LIPPOLD, 1954). Initially, to achieve a given tension, motor units were stimulated at a frequency of either 10 or 20 Hz; recruitment alone was used to vary tension. If recruitment alone could not achieve the desired target, once all motor units had been recruited, the frequency of firing of all motor units was increased until the muscle's maximum tension was reached.

Series 3: Finally, the ability of the muscle to maintain a given isometric tension to fatigue was assessed by measuring isometric endurance at tensions ranging between 10 and 100% of the muscle's maximum strength on each of four different cats. First, the maximum tetanic tension of the muscle was measured by stimulating the motor nerve sequentially at a frequency of 100 Hz. Next, the microprocessor utilised the pattern of recruitment and firing frequency (as described under 'series 2') necessary to cause the muscle to develop one of the 'target' tensions cited above. As the contraction was maintained, motor units began to fatigue. The resulting decrease in isometric tension was sensed by the microprocessor and compensated for by increasing first the recruitment, and finally, once all of the motor units were recruited, by increasing the frequency of motor unit stimulation. The total length of time the contraction could be maintained was called the endurance time. On any one muscle, a period of 30 min was allowed between fatiguing isometric contractions. The order of the presentation of the tensions were selected at random. In the same four cats, these data were compared to a similar set of experiments where stimulation was applied through the spinal cord.

4 Results

Series 1: The results of the first series of experiments are shown in Fig. 3. Ideally, the three electrodes should be able to generate a triangular voltage field, thereby electronically subdividing the motor nerve into three populations of neurons, as shown by the dotted lines in panel *a* of this Figure. However, the actual measured voltages showed significant cross stimulation between nerve bundles. To measure the degree of double and triple stimulation in some of these neurons, muscle action potentials were recorded from bipolar needle electrodes placed on 55 different muscle fibres from the medial gastrocnemius of two cats during sequential stimulation at a frequency of 10 Hz. Two stimulus amplitudes were chosen, these being those necessary for the muscle to develop $\frac{1}{2}$ and just maximal strength at a stimulation frequency of 10 Hz. When the stimulus amplitude was set at half maximal, double stimulation of motor units was seen in an average of 3% of the motor units sampled while triple stimulation was seen in less than 1% of the motor units sampled. In contrast, when the stimulation voltage was just maximal, the voltage field for each active electrode was similar to the one shown by the solid line in panel A of Fig. 3; double and triple stimulation of muscle fibres occurred in 47% and 3% of the motor units, respectively. Thus, instead of being stimulated at a frequency of 10 Hz, 47% of the motor units were being stimulated at a frequency of 20 Hz and 3% were being stimulated at a frequency of 30 Hz. The tension developed by stimulation of each electrode was measured by firing the three electrodes in turn at just maximal voltages and at a frequency of 0·5 Hz. The tension developed by each electrode under these circumstances was 38%, 44% and 38% of the muscle's maximum strength recorded when all three electrodes fired synchronously at this same stimulation frequency. To change the shape of the voltage gradient, and thereby reduce the double and triple stimulation, three additional electrodes were added to the initial sleeve electrode, as shown in Fig. 3*b*. Here, as in Fig. 3*a*, the stimulation electrodes are labelled 1, 2 and 3, while the additional electrodes are labelled G_{12}, G_{13} and G_{23}. These electrodes served only as reference electrodes. For example, Fig. 3*c* shows the electrode configuration used when electrode 1 became the active electrode (in actual operation the active electrode and all other associated circuitry were sequentially switched). When this electrode became active, reference electrodes G_{12} and G_{13} were allowed to float free while G_{23} was switched to earth potential. At the same time two $500\ \Omega$ resistors were switched between electrodes 2 and 3 and earth. This resulted in an electric potential gradient being established from electrode 1 toward electrode G_{23}, and, due to the series resistance, to a lesser extent toward electrodes 2 and 3. With a 1 V sinewave stimulus (frequency = 2 kHz), the resultant field has been plotted from multiple extracellular electrode recordings as shown for one cat in Fig. 3*b*. For simplicity, Fig. 3*b* only shows the voltages recorded between 0·9 and 0·5 V. As shown here, the stimulation field met the required specification of being nearly triangular in shape. Double and triple stimulation of muscle fibres was then tested as described previously. With half maximal voltages, double and triple stimulation was not seen in any of the motor units of the 2 cats

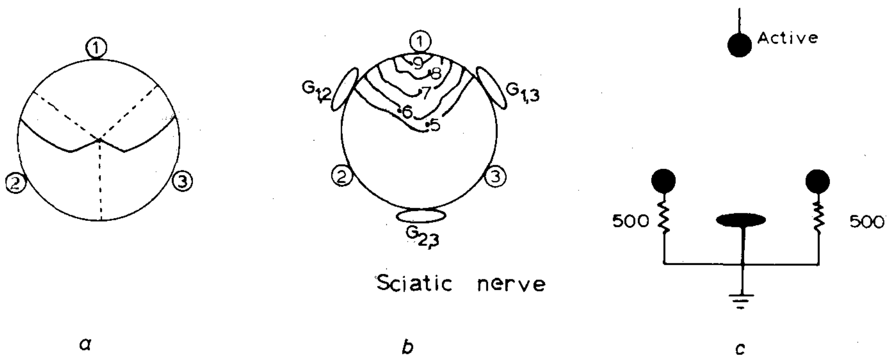

Fig. 3 Voltage fields created by sequential stimulation (a) without (b) with the additional earthing electrodes shown in (c) (see text for further description)

examined. With maximal stimulation voltages, double and triple stimulation was seen in 5% and 0% of the motor units, respectively. When the three stimulating electrodes were fired in turn at just maximal voltages, and at a frequency of 0·5 Hz, the tension developed by each electrode was 30%, 36% and 34% of the muscle's maximum strength recorded when all three electrodes were fired synchronously.

This electrode configuration was used to stimulate the muscle in the remaining experiments.

Series 2: The object of this series of experiments was to assess how tension could be developed and held during sleeve electrode stimulation. The pattern of recruitment and firing frequency used to develop maximum and submaximum tensions is described in Section 2.

The results of these experiments were similar for all four cats; therefore only the results of a typical cat are shown in Fig. 4. This Figure shows the tension developed by the medial gastrocnemius muscle for average tensions between 10 and 100% of the muscle's maximum strength. The initial stimulation frequency used here was 10 Hz, since this frequency is close to the initial motor unit firing frequencies found during voluntary isometric contractions of this muscle in the cat (OLSEN *et al.*, 1968). Tensions of up to 50% of the muscle's maximum strength could be developed by recruitment alone (achieved by increasing the stimulus amplitude). The target error due to the lack of twitch fusion generally was less than 2% of the muscle's maximum tension. To achieve tension greater than 50% of the muscle's strength, following the recruitment of all motor units, stimulation frequency was adjusted to achieve the target tensions. This resulted in the developed tension being progressively smoother at higher tensions; a frequency of 40 Hz was necessary to completely tetanise the muscle. To reduce the target error, an initial stimulation frequency of 20 Hz was tried. Such a manoeuvre reduced the target error at the lower tensions to less than 0·5% of the maximum strength; all other parameters remained constant. Under both experimental conditions, the largest stimulation voltage which was necessary to recruit all of the motor units was less than 1 V, while the greatest average current required by the electrode was 1 μA.

Series 3: Finally, to assess how well a tension could be maintained by the muscle, fatiguing isometric contractions were developed at tensions between 10 and 100% of the maximum strength of four medial gastrocnemius muscles, as shown in Fig. 5. Three experimental conditions were used: these being stimulation through the spinal cord (○) (since here electrical isolation between groups of motor units was assured), stimulation through the 6-wire sleeve electrode (●) and, finally, to assess the effect of double firing of motor units on isometric endurance, endurance was measured during stimulation with the original 3-wire electrode (▲). All endurances are shown ± their respective standard deviations. With all three types of stimulation there was a rapid reduction in endurance as the tension maintained was increased between 10 and 100% of the muscle's maximum strength. For a given tension, there was no statistical difference in endurance between spinal cord and 6-wire sleeve electrode stimulation. In contrast, without the aid of the three additional grounding electrodes, endurance was markedly diminished at almost all tensions examined.

5 Discussion

Peripheral motor nerves are cylindrical in shape

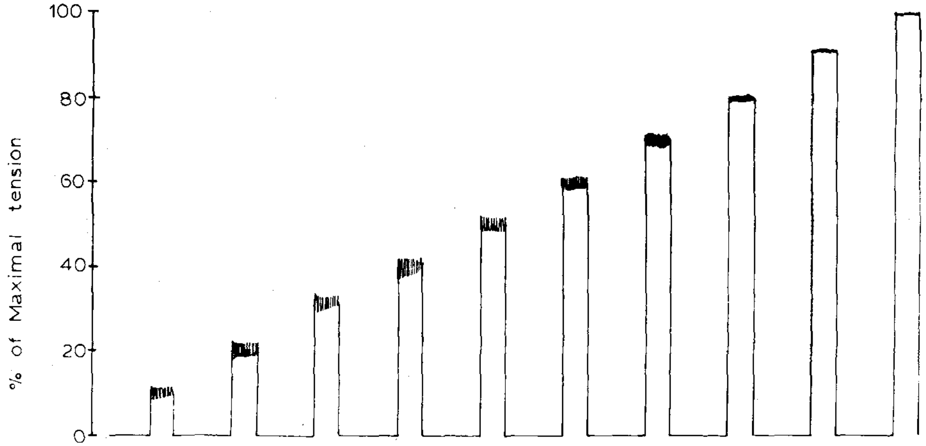

Fig. 4 Tension recordings from the medial gastrocnemius muscle of the cat during sequential stimulation with the sleeve electrode such that the muscle could develop tensions between 10 and 100% of its maximum tetanic strength

and contain a homogeneous mixture of motor and sensory nerve fibres (Eccles and Sherrington, 1930). Since the α motor neurons innervating a given skeletal muscle remain evenly distributed within the nerve throughout its length, the division of a mixed nerve by either surgical or electronic means should result in an equal distribution of motor units within the divided parts. This premise receives support in the present investigation where electronic division of the sciatic nerve into three parts and its subsequent stimulation resulted in a similar development of tension by each of the three motor neuron bundles. Furthermore, for any given tension, there was no significant difference between the isometric endurance measured during spinal cord and peripheral nerve stimulation with the 6-wire sleeve electrode.

The tension developed by muscle when stimulated through the 6-wire sleeve electrode array used in these experiments could be maintained smoothly for periods of time similar to that which is found in man during voluntary static effort (Petrofsky *et al.*, 1976). Although the tension can be maintained more precisely if the initial stimulation frequency of the computer was increased to 20 Hz, such an increase may reduce the isometric endurance by inducing neuromuscular failure (Brown and Burns, 1949). The initial frequency chosen then becomes a tradeoff between the precision of control and endurance. Although the 3-wire electrode is easier to make and requires considerably less circuitry, the endurance for fatiguing isometric contractions, particularly at the lower tensions, was significantly less here than for stimulation with the 6-wire electrode. This is most probably caused by neuromuscular failure, since, at fatigue, many of the motor units would be stimulated at frequencies of 2 or 3 times the final stimulation frequency of 40 Hz.

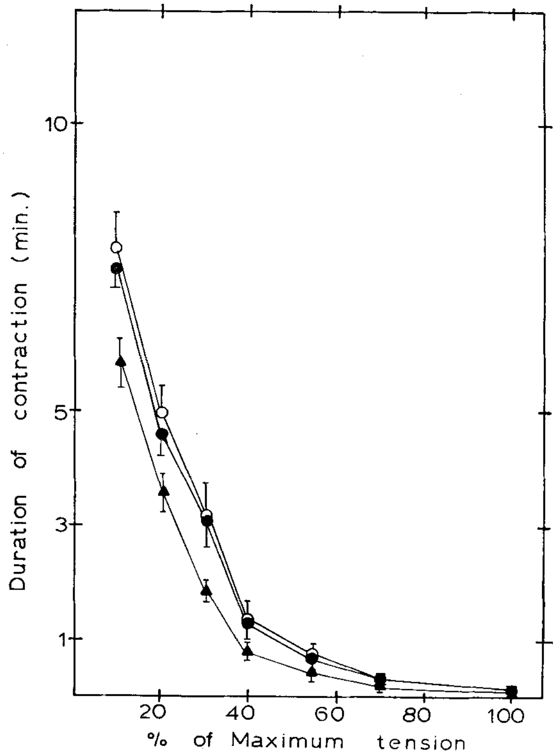

Fig. 5 Isometric endurance ± the standard deviation for fatiguing isometric contractions whose tensions were set between 10 and 100% of the maximum tetanic strength of the medial gastrocnemius muscle of four cats. The results of three experimental conditions are shown; these being stimulation through the spinal cord (○) and stimulation through the sleeve electrode with (●) and without (▲) the additional earthing electrodes

This electrode array offers a number of advantages for restoring movement following spinal injury. First, it is easy to apply, uses a small stimulation voltage, and consumes little power (voltages less than 1 V with a power consumption less than 1 μW). Although the electrode array described by Peckam (1976) is easier to apply, the stimulation voltages and currents are nearly 100 fold higher than those used here, causing tissue damage and high battery drain. Furthermore, because of the shortening of the muscle fibres during contraction, Peckam found it difficult to maintain a good electrode-tissue contact. Finally, the use of the microprocessor as a stimulator enables multiple electrode operation from a single microprocessor chip. In the system used here, the Intel 8080A microprocessor, 128 such electrode arrays will operate from the single computer. This computer can be programmed to provide smooth sequences of motion keyed from an external source such as the surface e.m.g. from chest or upper trunk muscles. Furthermore, by using one of the new low power microprocessors such as the RCA COSMAC, it should be possible to make the computer small enough and with a sufficiently low power consumption to implant the computer system and its own battery supply under the skin, as is commonly done with cardiac pacemakers.

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