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Effect of anaerobic and aerobic exercise promoted by computer regulated functional electrical stimulation (FES) on muscle size, strength and histology in paraplegic males

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Abstract

The influence of anaerobic and aerobic exercise, promoted by computer regulated functional electrical stimulation (FES) was evaluated in four paraplegic males. Quadriceps muscle bulk was monitored by serial computerised axial tomography (CT) scanning and histology by muscle biopsies from the vastus intermedius. Anaerobic exercise consisted of 60 degree straight leg raising against increasing weights (range 1.4–11.4 kg) over a period of ten weeks. Aerobic exercise consisted of pedalling a modified Monark bicycle ergometer at 50 rpm against a fixed load ranging from 0–3/8 kilopond (0–18.75 watts) over a period of eight months. In both exercise studies the same work was not achieved by each paraplegic. FES was regulated by a closed loop system which is not presently commercially available, the frequency of the sequential muscle stimulator was 40 Hz with a pulse width of 300 μs.

Quadriceps muscle area of both legs increased 62.7% ($p<0.01$) after anaerobic exercise; similar but less pronounced effects followed aerobic exercise. Histologically two distinct patterns were noted from the outset, one had normal fibre type distribution the remainder had marked Type 1 loss. Both exercise regimens failed to change these although the number of internal nuclei per 100 fibres steadily increased (from 7.0% to 13.8% to 26.0%) as did the % of fibres with internal nuclei (5.4% to 10.5% to 25.7%) throughout the exercise periods. The significance of these observations is not immediately apparent but may signify continuing damage which may be due to the eccentric rather than the concentric nature of FES promoted muscular contraction.

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Introduction

Maintenance of muscle mass requires continuous stimulation via the ∝-motor neurone. Disruption of such impulses that occurs following spinal cord trauma results in decreased muscle bulk, termed disuse atrophy.

It has been known for several centuries that isolated muscle preparations can be electrically stimulated to move. However clinical application of such a phenomenon has only relatively recently been developed which in part reflects advances in microcomputer technology which have made functional electrical stimulation (FES) a more practical proposition.

Preliminary evidence suggests that aerobic exercise, stimulated by computer regulated FES on a modified bicycle ergometer for 30 days increased endurance and average leg circumference by 1.9cm (Petrofsky et al, 1984). Bajd et al (1985) reported that a two-channel stimulator system regulating FES allowed practical crutch assisted walking in five individuals with incomplete spinal cord lesions.

These data are encouraging but the studies seem designed to evaluate the feasibility and perhaps practicality of FES rather than its influence on paralysed musculature.

It has been reported that in a study on ten paraplegics they displayed abnormal fibre type distribution below their spinal cord lesion with marked reduction of Type 1 (slow or red) fibres. In contrast above the lesion fibre type distribution was normal (Grimby et al, 1976). Comparable data have been published from animal studies. For instance cordotomy profoundly reduces Type 1 fibre numbers while increasing Type 2 (fast or white) fibres in guinea pig soleus muscle (Karpati and Engel, 1968). Interestingly Pette et al (1973) observed that in intact rabbits the composition of fast muscle could be altered to one resembling predominantly slow muscle by changing the pattern of electric stimulation.

The authors have therefore conducted a study in paraplegics to determine the influence of both anaerobic and aerobic exercise, promoted by FES, on muscle size, strength and histological appearance.

Subjects

Four paraplegic males who were involved in the *WALK Fund Project were studied and their clinical details are shown in Table 1. In addition to these details subject 2 was taking diazepam in a mean daily dose of 50mg which remained unchanged throughout the study. Only one (subject 4) exercised regularly prior to the study. This took the form of swimming three days per week for 30 minutes a session and again this was maintained constant.

Table 1. Clinical details of the four paraplegic men

Age (years)	27.3±6.4
Weight (kg)	67.9±4.5
Body Mass Index $\left(\frac{kg}{m^2}\right)$	20.5±0.5
Duration of paraplegia (years)	3.9±2.6

Figures=mean±SD

Methods

FES was administered via an as yet non-commercially available four channel stimulator. The pulse width was 300μs with a frequency of 40Hz. The electric stimulation used during anaerobic exercise ranged from 65–90 volts and for aerobic exercise 80–125 volts.

The muscle biopsy specimens were frozen in isopentane cooled to its melting point by liquid nitrogen. Cryostat transverse sections were stained at pH=9.4 to demonstrate myosin adenosine triphosphate activity so allowing identification of Type 1 and 2 fibres (Round et al, 1980). Sections were examined on a Magiscan image analysis system and fibre diameters calculated with an interactive computer program (Slavin et al, 1982). The fibre diameter represented the maximum distance across the lesser aspect of the fibre and when possible at least 100 fibres of each type were examined.

Protocol

Each paraplegic was studied on three separate occasions: initially prior to any exercise, after ten weeks of anaerobic exercise and finally after eight months of aerobic exercise.

Anaerobic exercise consisted of straight leg raising by extending the knee through 60 degrees against a gradually increasing work load. An individual cycle lasted six seconds (three up and three down) followed by six seconds rest with the weight adjusted to enable the individual to exercise for 15 minutes. Both legs were subjected to the same protocol. The weights ranged from 1.4–11.4kg during the course of this exercise which was undertaken for five days per week for ten consecutive weeks. Aerobic exercise consisted of pedalling at 50rpm on a modified Monark bicycle ergometer. This had a high-back seat with seat belt and shoulder harness for postural support, if required. Cycling was performed for 15 minutes for five days per week for a total of eight months. Exercise was carried out against a fixed load ranging from 0 to a maximum of 3/8 kilopond (0–18.75 watts). As with anaerobic exercise identical work was not performed by the subjects. Maximum work achieved by subject 1 was 18.75 watts, subjects 2 and 3, 6.25 watts, and subject 4, 12.5 watts. Figure 1 shows the position of the electrodes used to stimulate the various muscle groups which enabled cycling. Figure 2 shows the modified bicycle ergometer.

Initially and at the end of each exercise regimen the following were performed; a single quadriceps muscle biopsy which was taken from

Fig. 1. Positions of the electrodes used for FES.

*WALK: Charitable organisation concerned with promoting the provision of locomotion systems for paraplegic patients.

Fig. 2. Paraplegic subject on the modified bicycle ergometer.

approximately 5cm into the lateral mass of the muscle (Bergstrom, 1962) at the level of the femur via a UCH biopsy needle (Edwards et al, 1980). It was probable that fibres from the vastus intermedius were taken (Young et al, 1980). The same leg was used at each study.

Cross-sectional CT scans of both quadriceps muscle were taken and a representative picture is shown in Figure 3. Three separate cuts were taken although for the purposes of this paper only the one 6 inches from the lateral femoral condyle was used.

In addition to these investigations the paraplegics weight was recorded on a beam balance.

The protocol was approved by the Ethical Committee of the hospital and all individuals gave informed consent. Statistics were paired by t-test between the original results and subsequent ones.

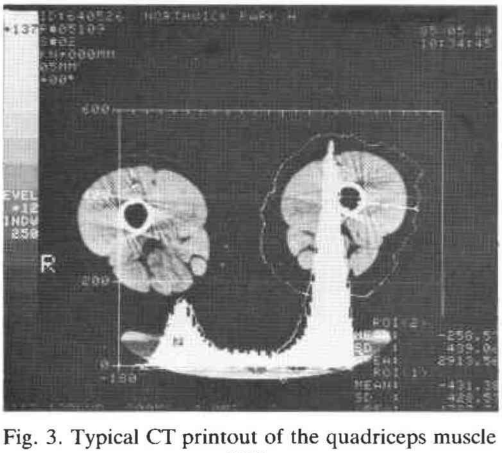

Fig. 3. Typical CT printout of the quadriceps muscle area.

Results

During the course of this study the size of the thigh obviously increased; this was more apparent following anaerobic exercise. However what was also noted was the friable nature of the biopsied muscle on all occasions. Histologically the paraplegics fell into two distinct categories; three (subjects 1, 2 and 3) having marked depletion of Type 1 fibres while the other had more normal distribution. These are shown in Figure 4. Neither of these patterns was influenced by the exercise. It was not possible to make any valid comment on the effect of exercise on Type 1 fibre number or diameter in the three paraplegics initially depleted while in the remaining individual these variables remained unchanged. However in all four, Type 2 fibre diameter increased progressively from $43.4 \pm 1.4\mu$ to $47.0 \pm 7.9\mu$ ($p =$ NS) to $61.3 \pm 8.5\mu$ ($p < 0.05$). The number of internal nuclei per 100 fibres steadily increased from 7.0 ± 5.4 to 13.8 ± 5.4 ($p =$ NS) to 26.0 ± 5.9 ($p < 0.001$). Likewise so did the % of fibres with

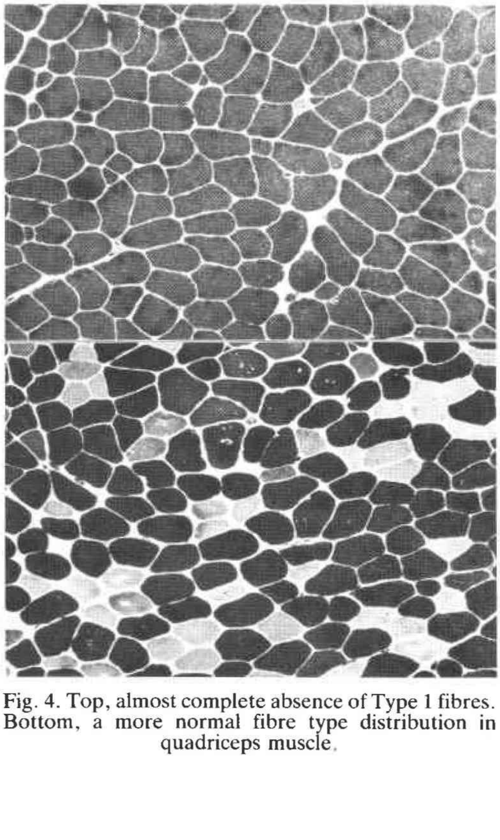

Fig. 4. Top, almost complete absence of Type 1 fibres. Bottom, a more normal fibre type distribution in quadriceps muscle.

internal nuclei from 5.4±3.8% to 10.5±3.7% (p=NS) to 25.7±3.1% (p<0.001).

The influence of both exercise regimens on total quadriceps area measured by CT scanning are shown in Table 2. Anaerobic exercise increased this area 63.5±23.3% (range 49.5–98.4%; p<0.01). In three paraplegics aerobic exercise resulted in a further but considerably smaller increase, 12.6±4.8% (range 8.5–19.3%). Subject 4 actually had a reduced area although this remained significantly larger than originally.

These paraplegics increased weight during the study from 68±5 to 70±4 to 73±4kg (p=NS) which was accompanied by a feeling of well-being.

Table 2. Changes in the quadriceps area of both legs assessed by CT scan following anaerobic (Ex 1) and aerobic (Ex 2) exercise.

Subject	BASAL	Ex I	Ex 2
2	2958	4528	5400
1	3224	6397	6943
4	3053	4671	4343
3	4337	6482	7161
Mean ± SD	3393 ± 639	5520* ± 1064	5962* ± 1334

Number=pixel unit *p<0.01

Statistics by paired t-test between basal area and those after each exercise. No statistical difference was found between exercise 1 and 2.

Discussion

This study has formally confirmed, by serial CT scans, preliminary observations that exercise stimulated by FES in paraplegics increases muscle bulk. This appeared more influenced by the shorter anaerobic exercise while the more prolonged aerobic activity had little additional effect on size. Both regimens increased the work performed by the paraplegics.

Although FES promoted exercise, increase in muscle bulk seemed to allow increased work, the maximum amount attained was considerably less than most non-trained, non-paraplegics would be expected to achieve (Edwards et al, 1977). Interestingly the level of work achieved appeared not to relate to the actual quadriceps area of both legs. Despite this there was a suggestion that the percentage increase of area was important with respect to work load. Subject 1, who had the greatest increase, approximately 115%, achieved the greatest work.

Histologically two patterns were noted from the outset of the study with three paraplegics having marked depletion of Type 1 fibres; the other had more normal distribution. These findings are somewhat at variance to data previously reported (Grimby et al, 1976). This study observed an almost universal absence of Type 1 fibres. It is possible that the minor differences between these findings may relate to the actual technique of muscle biopsy. It is known that fibre types are heterogenously distributed in muscle of mice (Susheela et al, 1968) and rats (Pullen, 1977). Likewise a study in man (Lexell et al, 1983) showed marked differences in fibre type from the vastus lateralis at various depths of the biopsy.

The study failed to demonstrate that fibre type distribution changed during FES promoted anaerobic and aerobic exercise. This is in marked contrast to findings in rabbits (Pette et al, 1973) and man (Munsat et al, 1976). This latter study showed that when muscle contracted isometrically Type 1 fibres increased in size (p<0.001) and percentage (mean increase SD=22.2±21.2%). In one individual a tenotomised muscle subjected to similar electric stimulation, and thus undergoing isotonic contraction, showed a different response. Type 1 fibre number decreased some 14.8% as did their mean diameter (p<0.001). Electrical stimulation was applied for far longer than the authors achieved which may be relevant to the differences in response between the studies. However no relationship was noted between the length of stimulation and degree of fibre type change (Munsat et al, 1976). In addition the type of electrical stimulation may be important (Hudlicka et al, 1982). Munsat et al (1976) employed intermittent stimulation at 33Hz while the authors used 40Hz via a sequential stimulator.

The most striking histological feature was the increase in the internal nuclei during the course of the study. The significance of this finding is unclear however. Certainly electrical stimulation is known to result in muscle fibre damage (Hudlicka et al, 1982). It has been suggested that the type of muscle contraction may be important with respect to possible muscle damage. Edwards et al (1984) postulated that eccentric muscular contraction which occurs during FES may be more deleterious than concentric contraction. The authors suggest that the increase in internal nuclei represents continued muscle damage although further work is required to confirm this. However despite such concern it has to be stressed that muscular work achieved did increase throughout the study.

In conclusion this study of computer regulated FES in paraplegic males shows measurable improvement in several variables of muscle bulk and performance. However future research needs to continue to refine this technique and to determine precisely the importance of the increase in internal nuclei before it is more widely used in the clinical setting.

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