THE EFFECTS OF PATTERNED ELECTRICAL STIMULATION ON THE CONTRACTILE PROPERTIES OF QUADRICEPS MUSCLE IN SPINAL CORE OF INJURED HUMANS

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ABSTRACT

The quadriceps muscles in 3 paraplegic volunteers have been trained by a 15 week period of patterned electrical stimulation. This produced significant increases in strength, fast muscle contractions and increased muscle endurance. These observations suggest that muscle fibre type may have changes. The muscle returned to its original state within 5 weeks after the training had stopped.

KEY WORDS: FES, Muscle atrophy, Muscle conditioning

INTRODUCTION

Wasting of paralyzed muscle through disuse or denervation is one major consequence of spinal injury. Whilst nothing be done to preserve denervated muscle in the long term it has been shown that electrical stimulation can reverse disuse atrophy et al 1973, 1980, Bajd et al 1983, Petrofsky et al 1984). Animal experiments have clearly shown that the mechanical properties of skeletal muscle can be profoundly affected by the applied pattern of stimulation. Large, faster contracting, easily fatigued muscles can be produced by brief periods of high frequency stimulation separated by long intervals of rest. Smaller, slower contracting, fatigue resistant muscles can be produced by prolonged or even continuous, low frequency stimulation. It is clear that the effects of stimulation are dependent on the stimulation frequency and temporal pattern (Rutherford & Jones 1988, Kernell et al 1987 a & b).

The demands made on muscle by functional electrical stimulation b(FES) for the restoration of standing or walking are great and varied. Quadriceps must produce brief, powerful contractions to lift someone from the seated position to the upright stance yet it must also be capable of considerable endurance to produce repeated lower force contractions needed during walking. Because of the relatively inefficient use made of the force generating capacity of the muscle by the imposed stimulation the metabolic demands during FES are greater than in normal persons doing similar things.

Thus, in preparing someone for standing and walking with FES it is necessary to improve the performance of their muscles by some training regime. However, little attention has been paid to producing the appropriate type of muscle by applying an optimal pattern of stimulation during training. We have addressed this problem by comparing the responses of muscle to three patterns of stimulation, prolonged *low-frequency, intermittent moderate frequency*, an *intermittent high frequency.*

METHODS

Patient selection

17 subjects with complete cord transaction were tested and 5 subjects with lesions between T_6 - T_{12} were selected on the basis of excatibility of the muscles Rectus Femoris (RF), Vastus Lateralis (VL) and Vastus Medialis (VM) via their motor point. Motivation and cooperation on the part of the subject were also important. Two subjects withdraw from the experimental programme after first few weeks.

Training Regime Parameters

A three channel stimulator was designed for subjects to use at home. Each channel operated independently to deliver the pulse train described below. Stimulation consisted of a series of rectangular pulses each lasting 0.3 ms. The amplitude was manually controlled up to produce a maximum of 130 mA. At each training session the amplitude was slowly increased to produce an effective contraction.

The stimulation patterns used were:

A.Rectus Femoris:	High frequency intermittent stimulation. 60 Hz, applied for 0.5 sec every 4 minutes
B.Vastus Lateralis:	Low frequency intermittent stimulation. 10 Hz, applied 10 seconds every minute
C.Vastus Medialis:	Low frequency prolonged stimulation. 10 Hz for 8 sec on and 3 sec off.

The subjects trained daily for periods of 2-4 hours for a up to 15 weeks. At intervals during this training period, and at intervals after training had stopped, the muscle function was assessed by isometric recording of muscle force.

The following tests of muscle function were made:

A. Programmed stimulation myogram. Electrical stimulation was applied continuously for 2 sec at 1, 10, 20, 50 and 100 Hz, whilst the isometric force was recorded.

B.Fatigue test. Electrical stimulation was applied continuously at 20 Hz for 3 minutes or at 80 Hz fro 30 sec. The isometric forces was recorded throughout this period.

C.Muscle bulk. The muscle bulk was estimated from measurements of the circumference of the thigh at 8 cm, 15 cm proximal to the patella and the mid-point of the thigh.

RESULTS

The observations in all three subjects were similar. For the purpose of illustration here a set of observations from one individual will be shown.

The extended low frequency stimulus pattern (C) applied to vastus medialis did not yield consistent results and we have excluded these from this report.

Both patterns of electrical stimulation (A,B) were successful in increasing the muscle bulk and the muscle force in all muscles tested. Figure 1 shows the circumference of the thigh measured at three levels before training, after 15 weeks of training and 5 weeks after training had stopped. Hypertrophy of the thigh muscles has caused a marked increase in circumference suggesting an increase in cross-sectional area of about 20%. The increased muscle mass did last long beyond the training period and 5 weeks after the end of training the limb had returned to its original dimensions.

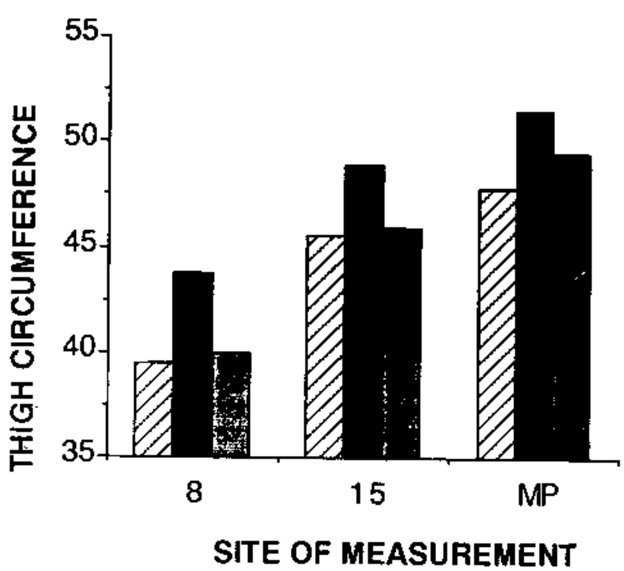

Figure 1. Thigh circumference measured at three sites, 8 and 15 cm above the patella and at the thigh midpoint, before training started (diagonal shaded columns), after 15 weeks of training (solid filled columns) and weeks after training had stopped (half tone column).

The mechanical response to stimulation of vastus lateralis is shown in Figure 2. The columns compare the force delivered by the muscle at each frequency before and after the 15 week training period during which the muscle was stimulated with the intermittent low frequency pattern. Note that there is a substantial increase in force at all frequencies tested even though the muscle was trained with only one frequency.

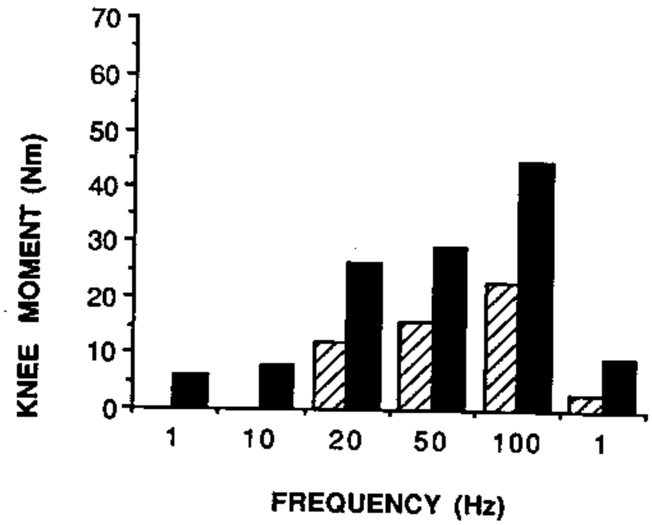

Figure 2. Forces developed by vastus lateralis during a programmed stimulation myogram before training (shaded columns) and after training (solid columns),

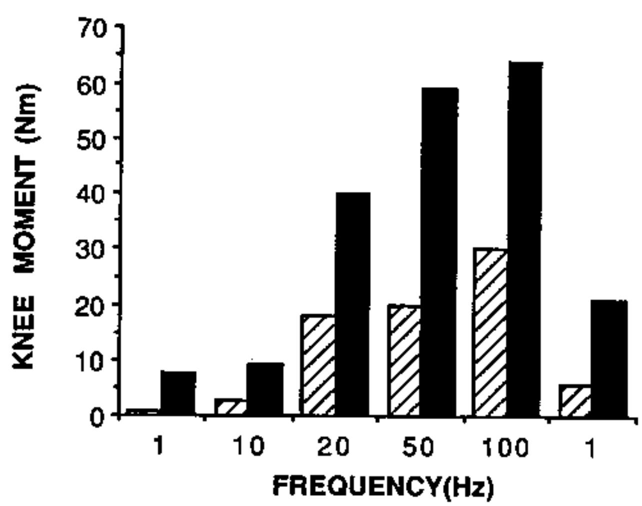

Figure 3. Forces developed by rectus femoris during a programmed stimulation myogram before training (shaded columns) and after training (solid columns).

Figure 3 shows the similar responses for rectus femoris which was trained for the same period with the intermittent high frequency pattern. The similar pattern to that seen previously is shown with substantial force increases is greater in this case. The greatest increase in force was at 50 Hz, where ir rose x3. Very large increases were also seen at 20 and 100 Hz.

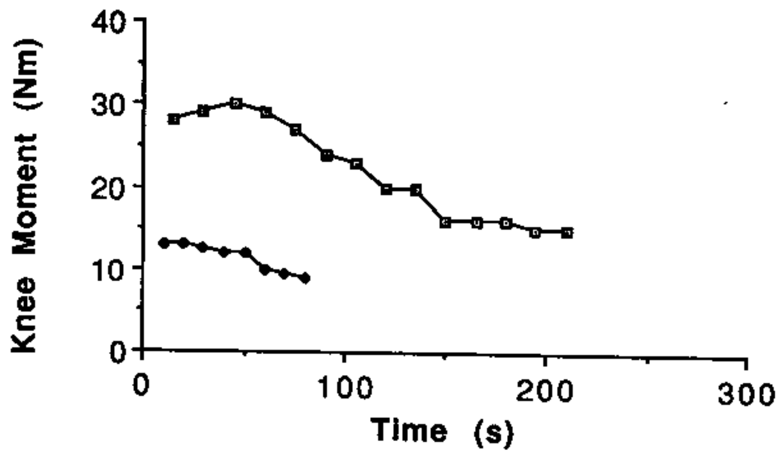

Figure 4. Force produced by vastus lateralis during continuous stimulation at 20 Hz. Force sampled every 15 sec. Open symbols after and closed before training.

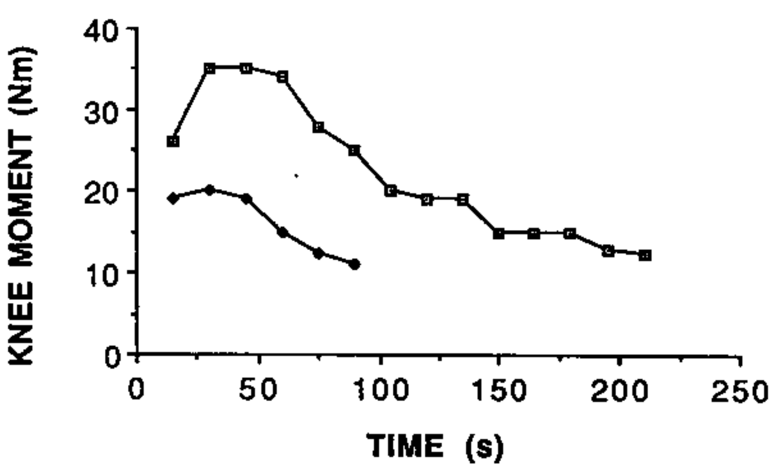

Figure 5. Force produced by rectus femoris during continuous stimulation at 20 Hz. Force sampled every 15 sec. Open symbols after and closed symbols before training.

There were also substantial benefits in the endurance of the muscle under stimulation. Figures 4 and 5 show the force produced by vastus lateralis and rectus femoris in response to continuous stimulation at 20 Hz. The upper lines show the muscle performance before training and the lower panels show the performance after training when high forces are produced for substantially longer.

DISCUSSION

It is clearly seen from these results that exercising muscles in paraplegics by intermittent stimulation has a strong effect on force production by the muscle. The training effect of the higher frequency intermittent bursts used on rectus femoris appears to yield the greatest effect. The muscles also appear to be faster contracting after the training. Note that there are substantial increases in force production as the stimulation frequency increases from 20 to 50 Hz and then from 50 to 100 Hz. This is evidence that the tetanic fusion frequency is higher after training. This effect is more evident in rectus femoris than in vastus lateralis .

There may be a functional advantage in this in that muscle became strong enough to lock the knee in extension during stance after training whereas they were too week to exert that action initially.

The increased endurance during continuous stimulation at 20 Hz is surprising since most effective training regimes are patterns which might be expected top train the strength preferentially. Nevertheless, there is a significant improvement in fatigue resistance. This also has a functional significance in that muscles can sustain their forces for much longer periods and so lengthen their period of use.

There are many known causes of muscle fatigue (Edwards et al 1977, 1981), each likely to limit muscle performance and endurance in different circumstances. The precise cause of fatigue in FES type contractions has never been clearly identified. Observations made during this study have revealed that the amplitude of the M wave recorded with surface electrodes falls quickly during stimulation. In addition, electron myography of muscle material from paraplegic muscle shows an unusual appearance of the T-tubule system. These finding point to a failure of excitation-contraction coupling being a major cause of fatigue. Preliminary histological studies have shown that the biopsy samples taken after training contained predominantly 2a fibres. This would fit well observed findings of increased force, higher tetanic fusion frequencies and improved endurance. Though the extent to which training induced changes in the metabolic profile of the muscle fibres are correlated with changes in the security of electrical excitation remain to be established.

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