Standing, stepping and cycling for a T9 paraplegic with a Lumbo-sacral Anterior Root Stimulator Implant.

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Abstract
Root stimulation responses and effects of training were described for one female subject with a complete T9 spinal lesion. She has a 12 channel stimulator implant with electrodes on the anterior L2 to S2 spinal roots bilaterally.

For standing, lower lumbar and sacral root stimulation extend knees and hips respectively. The primary clinical aim for the patient to stand under her own control with sufficient stability to have one hand free for reaching has been attained. The patient was authorised to use the implant controller for that purpose at home in January 1996. Standing is limited to a maximum of about 3 minutes at a time by hip flexion, the reasons for which are still under investigation.

For stepping, the upper lumbar roots have been used to swing the leading leg forward, returning to lower lumbar and sacral root stimulation for the stance phase. Leg adduction during the swing phase has prevented use of this function outside the laboratory. This hip adduction can be adequately reduced temporarily by blocking the obturator nerves with Marcain. A permanent surgical solution is under consideration. She has taken 24 steps at a time using the stimulator.

Leg powered cycling has been achieved using a recumbent tricycle. For each leg, alternate lumbar and sacral root stimulation was used to push the corresponding pedal through half a turn. She has cycled 1200 metres at a time at about 12kph.

Index Terms: Standing, walking, cycling, paraplegia, Functional Electrical Stimulation, spinal root stimulator implant.

I. Introduction

Numerous attempts to restore leg function in paraplegia by Functional Electrical Stimulation (FES) have been made, including [1] for standing/walking with peripheral nerve implants and [2] for cycling with surface stimulation. The purpose of the British Medical Research Council's Lumbo-sacral Anterior Root Stimulator Implant (LARSI) project, as outlined in [3] was to evaluate root stimulation responses and determine their suitability for restoring leg function in paraplegia. The lumbar roots innervate the medial and anterior aspects of the legs and the sacral roots innervate the posterior and lateral parts. Each muscle group may be innervated by several roots. We also wished to obtain sufficient utility for the patient to be encouraged to maintain significant daily leg muscle training, especially as others have found health benefits from sustained regular FES exercise. For instance, improvements in bone mineral density were reported in [4].

Our present paper is an update on work already described in [5], [6], [7] and [8]. The results given are from the first patient to receive an implant in this project.

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II. Methods

In December 1994, a complete T9 paraplegic was implanted with electrodes for stimulating the anterior spinal roots from L2 to S2 bilaterally. The stimulation hardware needed was developed from that of [3]. Since the surgical wounds healed shortly after the implantation, there has been no break in the skin: the implant is controlled from outside via RF coupling. Because of the complexity of the innervation, automated stimulation responses were obtained using the multimoment chair, as described in [3], which measures all seven joint moments for each leg. Thousands of stimulation patterns (out of the millions of possible) were tried. The best patterns for standing and walking were then chosen and verified in functional testing.

For standing, lower lumbar root stimulation stabilizes the knees and sacral root stimulation stabilizes the hips. The patient has 'UP' and 'DOWN' buttons on her standing/walking frame to select the desired getting up or sitting down action. If the legs become fatigued during a stand, the patient can increase strength by pressing the 'UP' button again.

For stepping, upper lumbar root stimulation swings the leading leg forward, reverting to the standing pattern at the end of the stride. Each pace is initiated by the patient pressing a switch on the relevant handle of her walking frame.

For cycling in a recumbent tricycle, we stimulate, for each leg, alternate lumbar and sacral roots to push the corresponding pedal through half a turn. To obtain the exact patterns of stimulation required, some 300 pedal force responses to stimulation were measured as the crank angle was varied in 16 increments around the complete cycle. For the cycling stimulation program, crank angle is measured by a shaft encoder and the relevant stimulation pattern is then read from a look up table, in the stimulation controller, based on the pedal force results. The effect of the dynamic response of the muscles was accounted for by noting the delay between stimulus at the spinal root and the consequent peak muscle force generated. In practice, having measured the pedaling speed, the crank angle used for the look up table is adjusted forward by the above delay. The resulting phase advance in stimulation is proportional to pedaling speed. Power output was estimated from a knowledge of the combined weight of rider and tricycle, rolling resistance, road gradient and cycling speed.

III. RESULTS

Our patient shows broadly similar lumbo-sacral root motor responses to those expected from the work of others, such as [9], including a tendency for responses to be somewhat asymmetrical. As can be seen from [8] most movements are indeed innervated by several roots (eg Right iliacus gave strong EMG from stimulation of the four roots from L2 to L5). This spread of innervation was, if anything, greater than expected and made selection of the desired muscle responses difficult. The responses were found to be very dependent on the daily training program used and some undesired effects, such as ankle inversion were successfully "trained out". The patient maintains training at about 40 minutes daily, having had the stimulation controller at home for this purpose since December 1994.

It has been only too obvious that joint angles can very greatly affect joint moments. We have therefore been obliged to use one stimulation pattern for getting up from the wheelchair, while the knees and hips are still somewhat flexed. Then, for standing erect, we have had to use a different pattern.

At home she can stand at will for up to 3 minutes, with sufficient stability to have one hand free for reaching. She has used this function to reach spice jars on the top shelf in her kitchen. Standing time is limited by hip flexion, particularly of the right hip. Temporary blockade of iliacus or rectus femoris with local anaesthetic (Marcain) did improve right hip posture. However the rectus femoris block eliminated too much knee extension for safe standing. It is just as well the blockade was temporary. The detailed causes of the hip flexion are still under investigation.

As described in [10], she has, in the laboratory, taken 24 steps at a time, limited by hip adduction. Her legs tend to cross over as she walks and generally assistants have to ensure her feet are kept apart to prevent her tripping over. We have had modest success at training up the strength of the abductors to reduce this problem but, particularly on the left, the improvement in muscle response has been inadequate. The hip adduction has been eliminated temporarily by blocking the obturator nerves with Marcain. She was then able to walk with the feet separating rather than crossing. She described the effect as her "John Wayne" impression, as though she had been horse riding for too long. Satisfactory walking is currently only possible for the two hours before the anaesthetic wears off.

IV. CONCLUSIONS

LARSI can provide a paraplegic with three functions: standing, stepping and cycling. The stepping function clearly cannot yet be used outside the laboratory, although the other two functions have already been in use at home. Improvements in standing and stepping await a permanent surgical solution for the excess hip flexion and adduction.

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