ABSTRACT
In December 1994 a woman with a complete T9 spinal lesion had a 12-channel stimulator implanted with electrodes on the anterior L2 to S2 spinal roots bilaterally. Some restoration of cycling ability has already been demonstrated in [1] and [2]. She achieved leg powered cycling for 1.2km at a time using a recumbent tricycle in May 1998. The cycling system has since been developed further. Initially, static measurements of pedal forces due to stimulating each implant channel (and also some lumbar and sacral root combinations) were plotted against cycle crank angle. From these tests, stimulation patterns were derived to give the most positive static pedal forces for every crank angle. These stimulation patterns were then used in dynamic cycling tests, the delay between stimulation and muscle response being accounted for by advancing the crank angle for selecting patterns by an angle equivalent to 0.25 seconds at the measured speed. Co-ordinated pedalling was then possible at up to 86rpm. To optimise control program further, we made dynamic pedal force measurements, both on our paraplegic subject and an able-bodied cyclist for comparison. We found that a reduction in simultaneous lumbar and sacral root stimulation improved power output during rapid pedalling.

Key words: Cycling, paraplegia, Functional Electrical Stimulation, spinal root stimulator implant.

INTRODUCTION
Numerous attempts to restore leg function in paraplegia by Functional Electrical Stimulation (FES) have been made, including [3] for standing/walking with peripheral nerve implants and [4] 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 [5] was to evaluate root stimulation responses and determine their suitability primarily for restoring standing in paraplegia. In the current project we seek to add the function of cycling in a recumbent tricycle. We hope 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 (eg bone density improvement [6]).

This paper is an update on work already described in [1], [2] and [7 to 9]. The results given are from the first patient to receive an implant in this project.

METHODS
In December 1994, a complete T9 paraplegic was implanted bilaterally with electrodes for stimulating the anterior spinal roots from L2 to S2. The stimulation hardware needed was developed from that of [5]. 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.

When cycling, the ankles are stabilized by Ankle Foot Orthoses (AFOs) attached to the tricycle’s pedals. To choose the correct patterns of stimulation, propulsive pedal force responses to stimulation (ie right angles to the crank) were measured at 16 crank angles for 18 different patterns. For the 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’s memory. The effect of the dynamic response of the muscles is accounted for by noting the delay between stimulus at the spinal root and the consequent peak muscle force generated. A crank angle phase advance in stimulation, which is proportional to pedalling speed, is obtained by angle used for the look up table being adjusted forward by this delay.

Initially, power output was estimated from the combined weight of rider and tricycle, rolling resistance, road gradient and cycling speed. Dynamic measurements of crank angle and crank strain (via RF telemetry from strain gauges in the cranks) give more direct power estimates. Crank strains were also monitored with able-bodied cyclists for comparison.

Several variants of the cycling program were tried, while monitoring power output. The best of these programs was then chosen for use. To further assess the cycling program, measurements of the net static pedal forces available from stimulation were added to calculated forces due to the weight of the limb segments and the AFO/pedal combination, to obtain a predicted plot of crank strain versus angle. This was then compared with the actual crank strains obtained in cycling.

RESULTS

Our patient has had the tricycle home for regular static leg powered cycling exercise (with the drive wheel supported on a “resistance trainer” stand) since April 1998. In May 1998, with the trainer removed, she was able to cycle with the aid of her implant for over a kilometre for the first time. She then cycled on gently undulating open road for 1200 metres at a time with a mean power of 34 Watts, corresponding to a speed of 12kph on level ground.

She has subsequently reported a 3km. cycling ability. The patient maintains training at about 30 minutes daily, alternating cycle training with that for standing.

Static pedal forces in response to stimulation are shown in Figure 1. Having tried muscle response delay allowances from 100-300mS, we found that the best power output was obtained with a 0.25 second advance. At 60rpm this corresponds to adding 90 degrees of phase-advance to the crank angle measurement. By removing some of the co-activation in lumbar and sacral root stimulation that seems necessary to obtain the best static pedal forces in Figure 1, we found that power output at higher pedalling speeds was improved. Our patient could then pedal in a co-ordinated manner at up to 86rpm. Figure 2 shows dynamic right crank strains at increasing pedalling rates in response to stimulation. The spikes on the
response seen at higher angular speeds seem to be due to knee flexion reflexes, which fortunately aid the cycling motion, but disturb the measured phase of crank strain compared with the predicted response shown in Figure 3. Below 60rpm, however, Figure 4 shows that predicted and measured dynamic responses correlate well in both phase and amplitude. We found that the crank strain data from an able-bodied cyclist also closely matched that of our paraplegic subject at these lower speeds, when cycling with the same speed and resistance.

Figure 2: Position and crank strain versus time for LARSI cycling.

Figure 3: Measured and predicted crank strain, LARSI cycling at greater than 60rpm.

Figure 4: Measured and predicted crank strain LARSI cycling at less than 60rpm.
CONCLUSIONS

The stimulation program used for our paraplegic subject produces cyclic changes in torque which match ‘normal’ cycling closely up to 60rpm. Considerable work remains on optimising the cycling stimulation program further. The present program nevertheless shows LARSI can already provide a paraplegic with a useful and enjoyable leg powered cycling capability.

ACKNOWLEDGEMENTS

We are grateful to the Wellcome Trust, Stanmore Royal National Orthopaedic Hospital (RNOH) and INSPIRE for funding this work. We are also grateful to the following contributors:- R. Fitzwater, RNOH, for assembly shaft encoder modules; From Salisbury District Hospital:- E.Askew and S.Morant, for the AFOs; A.Lamb, for cycle equipment design; I.Swain, for planning and encouragement; S. Crook and P.Taylor, for useful advice and J. Norton and P.Wright, for static pedal force measurement. Most of all we would like to thank our volunteer patient and our families for their tolerance of the long hours of testing.

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