1 Introduction

HIGH-LEVEL spinal cord lesions at C4/C5 level result in total loss of upper and lower limb function. Shoulder girdle movements are generally present in the C4 lesion level quadriplegic generated by the upper trapezius and the rhomboid muscles.

Improved post-trauma and subsequent medical care in recent years has resulted in a substantial and increasing population of high-level quadriplegics. The quadriplegic, on his return to the home environment from the rehabilitation centre, requires a full-time attendant. Supplementary means to improve the quality of life or the independence of the quadriplegic include trained monkeys, used in the home for carrying out simple tasks. Table-top and fully mobile robot systems are under development in various research centres. A mouthstick has proved the most effective functional aid, having been used for example for keyboard (computer, typewriter) operation and for painting. Environmental control systems for operating electrical appliances are in fairly common use controlled by vocal commands, puff-suck pneumatic command systems and mouth-operated joysticks. Similar wheelchair control systems are also available.

Functional movements may be obtained from the arms themselves using ball-bearing feeder supports, which support the forearm at a single point, allowing it free linear movement in a horizontal plane, and also free rotation about this point, controlled by shoulder girdle and upper body movements transmitted through the arm. This allows a certain control and range of arm motion. Forward reach is usually unobtainable. Utensils may be clipped to the hand, restoring a limited amount of function. This is not altogether acceptable for many quadriplegics for several reasons:

(a) Having utensils clipped to the hand is detrimental to self image and often unacceptable outside the rehabilitation department.
(b) The inability to pick up and release utensils leaves the quadriplegic totally dependent on the attendant for changing utensils.
(c) Lack of forward reach limits the working region in which the hand can function.
(d) Although the shoulder and elbow joints articulate, the finger, thumb and wrist joints are not exercised and can degenerate.

A solution which allows the active prehension and release of utensils is the pneumatic powered orthosis. This device is used with the ball-bearing feeder and passively articulates the fingers and thumb to generate one type of hand-grip.

None of these solutions, however, provides for active use of the muscles. An unused muscle often degenerates over a period of time, either becoming atrophic or spastic. This may cause secondary bone and joint deterioration and can force the arm into a claw configuration. Daily passive physiotherapy can keep the limb comparatively healthy, but is time consuming and expensive, requiring a one-to-one ratio of man-hours to treatment time, and often the quadriplegic receives far too little. The optimal form of physiotherapy is active functional limb movement. Here the muscle contracts actively while generating useful function: an incentive to regular use. Functional neuromuscular stimulation (FNS) can generate active limb movements. Over the last few decades control and refinement of these stimulation-generated movements have been applied in various research centres to muscles of body limbs and organs to generate or enhance their impaired function.

Development of FNS systems for the upper limb has been applied to the hand and to the wrist joint. Stimulation of the biceps for elbow flexion has also been attempted, although systems suitable for up to C5/C6 level...
quadriplegics (where voluntary arm movements are still possible and the hand and wrist only are paralysed) have been reported (Peckham and Mortimer, 1977; Peckham et al., 1980; 1981; Crago et al., 1986; Handa et al. 1985; 1986; Pasniczek and Kiwerski, 1983; Ruidel et al. 1981; Vossius, 1986). These systems generate hand function (prehension/release) while whole arm movements are carried out voluntarily. Control of the C5 stimulation system involves a comparatively small number of command signals, whereas a fairly large number of possible control sites exist for input of a command signal by the system user. The higher and more complete the level of paralysis, the fewer are the residual voluntary movements available for articulation of the arm, and the larger are the number of movements which must be generated and controlled by the stimulation system. The complexity of the input commands must be increased, while fewer command sites are available for direct user control of the system.

Handa et al. (1987) and Hoshimya and Handa (1988) recently reported work on the FNS of a C4 quadriplegic subject. The system is semi-implanted, using intramuscular electrodes, a percutaneous connector, and an external stimulation system with microprocessor control. A puff-suck unit inputs the commands, and complex co-ordinated movements such as handgrips are based on recorded EMG patterns from healthy limbs. Four muscles of the elbow joint are stimulated to generate elbow flexion. The arm is supported on a ball-bearing feeder, and its plane of motion is angled upwards towards the mouth. To date drinking through a straw and the application of make-up to the face have been achieved.

A FNS-based hybrid system suitable for lesion levels of C4 and above has been under research and development since the mid-1970s in Beer Sheva (Nathan, 1979; 1981; 1984a; 1984b; 1986). The system was first successfully applied to the author's own (non-paralysed) arm in 1984. In 1985 a clinical programme was initiated with the opening of the FNS research laboratory in the Spinal Injuries Rehabilitation Department of the Sheba Medical Centre in Tel Aviv. The system was further developed, and applied to the arms of two C4/C5 level quadriplegics.

2 The stimulation system

Fig. 1 shows diagrammatically the stimulation system. Vocal commands are input through a voice-recognition system to an Apple II microcomputer. The microcomputer controls, through its D/A output, a 24-channel stimulator built in Ben-Gurion University. The stimulator generates square wave compensated double pulses at constant current. Pulse width and delay are parameters controllable from the computer, but throughout this work were fixed at 0.3 ms and 0.7 ms, respectively. Dual parameter control of stimulation intensity has been programmed into the stimulator. The stimulation current is modulated over a range of 0-40 mA at a constant pulse frequency of 15 Hz. The current level on reaching the maximum is now held at 40 mA while the pulse frequency is raised from 15 to 50 Hz. This progressively recruits the motor units in the target muscle at their lowest tetanic firing rate. The low firing rate keeps the muscle fatigue to a minimum.

To further increase the force generated, the firing rate is then increased, although at these higher pulse frequencies the fatigue rate is high (Nathan, 1984a). This dual-parameter modulation of stimulation intensity is controlled either from the computer program software or from a remote manual control unit. The manual control unit has an additional function. While the stimulator is being controlled from the computer software, the manual control unit can be set to a lower maximum current level on each channel, to the saturation current level for the muscle it controls, or to a safe current level which will not cause overflow to non-target muscles.

The stimulator output passes through a cable to 12 bipolar electrode pairs held in place by an elastic mesh sleeve. The electrodes are 5 mm x 17 mm and of conduc-