NATURAL AND ARTIFICIAL SENSORS IN NEURAL PROSTHESES

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Contained within the human hand and the forearm muscles that control the hand are thousands of miniature sensors. When a normal individual grasps an object, these transducers send information to the spinal cord and to the brain about the temperature, texture and weight of the object, about where the object is in space, the distribution of grasp pressure across the surface of the hand, and sometimes pain producing characteristics. If the spinal cord is interrupted in the neck, these sensory signals are interrupted along with the motor signals that normally control the muscles. Currently, research groups throughout the world are attempting to restore lost function to neurologically disabled individuals, and the devices they develop are known as neural prostheses. Functional electrical stimulation (FES) is the technique of utilizing electrical stimulation to activate excitable tissue and functional neuromuscular stimulation (FNS) is the specific term used to designate electrical activation of paralyzed muscles.

Neural prostheses can be used to transfer information into or out of the nervous system. An example of a neural prosthesis that involves inward information transfer is the cochlear implant for the sensory deaf. These individuals have lost the transducers that convert the pressure variations of the acoustic environment to the electrical signals that are utilized by the auditory nerve between the inner ear and the brain. Current cochlear implants utilize one or more electrodes implanted in the middle or inner ear to electrically activate auditory nerve fibers. The electrodes are connected to electronic circuits that include a microphone, speech processing circuitry, and appropriate stimulus waveform generators.

Another class of neural prostheses are being developed to assist in evacuation of the urinary bladder. Certain individuals with lesions of the brain or spinal cord lose the ability to voluntarily evacuate the bladder. This is not only a psychological and social problem but also can result in life threatening infections of the urinary system. Many of these individuals lose not only the ability to activate the detrusor muscle that contracts the bladder, but they also are unable to sense when the bladder is full. The sensors in the bladder are essentially pressure transducers with variable thresholds. If the bladder is slowly distended, the transducer threshold is high and the bladder can hold a greater volume before signals of discomfort are generated and sent to the central nervous system. However, if the bladder is rapidly distended, the transducer threshold is low and and the message to empty the bladder is transmitted despite relatively low bladder volumes.

Ideally, a bladder evacuation prosthesis would derive bladder pressure signals from the natural bladder transducers. At the present time, this is not possible. The sensory nerve fibers from the bladder are very fine, and it is extremely difficult to detect the microvolt level signals that accompany their activation. In lieu of utilizing the natural transducers, an artificial bladder pressure transducer is needed. This implantable transducer should detect the differential pressure across the bladder wall (i.e., between the bladder interior and the abdominal cavity). It should be able to detect pressures as low as 5cm H_2O and as high as 120cm H_2O (1). The design and packaging must be such that the transducer is not affected by the saline environment or by the 100-500 micron thick fibrous encapsulation that occurs around implants. It is conceivable that the implanted transducer might include circuitry to determine the rate of increase of bladder pressure, but such signal processing is probably more easily accomplished after the basic transducer signal has been transmitted outside of the body. The simplest method of removing the signal is by direct wires with percutaneous connectors. However, these connectors can serve as an entrance route for pathogens with subsequent infections. Safer techniques include interrogation of transducer status by techniques such as grid dip oscillators or active inductive or electromagnetic transmission from the transducer.

The challenges in developing methods of activating paralyzed limbs in quadriplegic and paraplegic individuals have similarities to the bladder evacuation problems but are much more complex. People who have sustained spinal cord injuries in their necks are generally left with little or no motor control of their hands, trunks or legs, and little or no sensation in these parts. The feasibility of using FNS to activate their paralyzed hand muscles has been demonstrated in a clinical laboratory environment but not in everyday living outside of the hospital (2). Microprocessor controlled, multichannel stimulators have been developed. These take care of the bookkeeping requirements of selecting the order in which muscles are to be activated and the stimulus parameters after the paralyzed individual has specified the type and degree of motion desired. Transducers that detect voluntary contractions of nonparalyzed muscles or the position of nonparalyzed body parts are used for the derivation of the voluntary control signals. Except for visual feedback about the position of the hand, the system is essentially open loop.

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This makes control rather slow and tedious as corrections must be made for non-linear relationships between muscle force output and stimulus levels, muscle length and muscle fatigue. The users must concentrate on a task rather than use their visual system to periodically sample the status as normal individuals do.

It is tempting to consider methods of making connections with the natural sensors in the skin, joints, and muscles of paralyzed individuals since these sensors are intact and are sending signals to the injured spinal cord. Under laboratory conditions in which upper extremity movement is restrained, fine wire electrodes have been introduced into human nerve trunks and signals from most of the types of transducers in the hand have been detected (3). It has not been possible to chronically record from these nerve trunks under unrestrained conditions. However, Loeb and his colleagues have developed a technique for recording from the rather large cell bodies of cat sensory neurons in the dorsal root ganglia for periods of several months (4). At this location, the relative movement of the neurons with respect to the surrounding tissues is reduced and the extracellular signals generated by the large cells are easier to record. It is conceivable that this technique might some day be developed to the point where it could be utilized in a FNS system.

Without the ability to tap the natural sensors, artificial transducers are being explored. It is the consensus of control engineers working with FNS for restoration of hand grasp that finger position relative to the thumb and the force on the grasping surface of the thumb are the two most important pieces of information needed. One concept is to incorporate transducers into a glove as illustrated in figure 1.

The original idea was to use a flexible piezoelectric polymer such as polyvinylidene fluoride (PVF_2) for both position and force measurements. Attempts to utilize the polymer as part of an ultrasonic ranging system for position measurements were defeated by the inability to achieve usable signal to noise ratios and by the fact that grasped objects block the ultrasonic signal. However, the possibility still exists of using the PVF_2 to measure force.

Firm specifications for hand position and force transducers have not been established, but tentative values for laboratory evaluation of closed loop control systems are given in Table I. Transducers based on differential transformers for position measurements and strain gauges for force measurements have been fabricated to these specifications and are now being tested. However, they are not miniature and cosmetically acceptable nor have they been designed to be durable enough to withstand the abuse that they will incur in the home environment.

It is anticipated that future FNS systems will be totally implanted. If they are closed loop systems and if suitable methods cannot be developed to tap the natural sensors, then artificial implantable transducers will need to be developed. Walmsley and Loeb have designed and tested implantable tendon tension and joint position transducers in cats (4). Although these transducers have a lifetime of several months, transducers for use in FNS systems must have much longer lifetimes and must be able to detect the force distribution across the grasping surfaces. To the author's knowledge, no attempt has been made to do this with implanted artificial transducers.

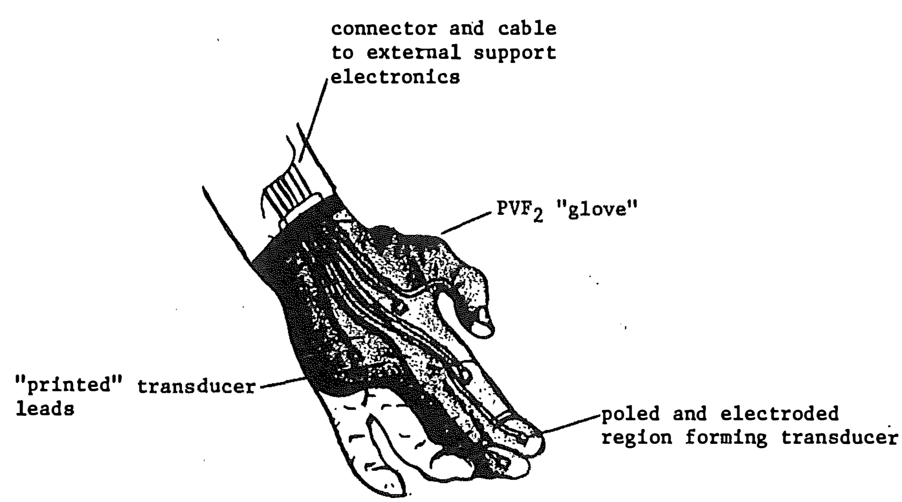

Fig. 1: Concept of force transducers incorporated into a modified glove (Courtesy of Dr. Andrew Schoenberg)

TABLE I

	Force transducers	Position transducers
Resolution	0.1 newtons (at less than 10 newtons and 1% at greater levels)	1 mm (or 0.3 degrees of angle, whichever is smaller)
Range	0.1 - 80 newtons	1-120 mm
Frequency response	d.c. to 100 H_z	d.c. to 100 H_z
Response delay	less than 2 msec	less than 2 msec

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