

## A Modular Approach to Sensing Limb Position in FES Patients

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### Abstract

*Information about limb posture and movement promises to provide a rich source of voluntary command signals and feedback for regulation of FES, but only if the sensing technology does not encumber the patient. We are developing a variety of prosthetic proprioceptors that can be incorporated into BION® wireless, injectable neuromuscular stimulators. Multiple implants will be distributed nonorthogonally in many muscles where their position and orientation will shift with limb posture. This gives rise to an information processing problem not unlike that which the brain must solve using signals from biological proprioceptors.*

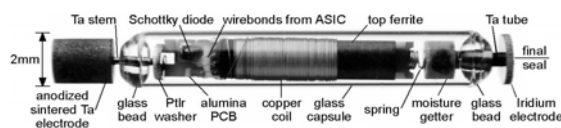
### 1 Introduction

As clinical applications of FES become more ambitious, they will become more dependent on prosthetic interfaces that provide sensing functions as well as neuromuscular stimulation. Information about residual voluntary movement of some limb segments is likely to provide a particularly useful source of command signals because such control is likely to be accompanied by conscious perception of movement and loading. Information about the motion of the limb segments achieved by FES of paralyzed muscles will be necessary to replace the normal regulation of movement by spinal “reflex” circuitry.

Obtaining accurate and complete information about limb motion in a laboratory environment remains challenging; obtaining such information under field conditions of FES is daunting. In particular, it will be necessary to avoid burdening patients and caregivers with externally worn components that are difficult to don and doff, exposed to mechanical damage, and unsightly. Such considerations essentially eliminate conventional laboratory technologies such as imaged markers and electrogoniometers.

### 2 Methods and Results

BION™ wireless microstimulators receive power and individually addressable command signals from an externally worn RF transmission coil [1]. One or more BIONs can be injected into various muscles or near muscle nerves to provide precise and selective control of the intensity and temporal patterning of individual muscle activation. Additional BIONs can be injected at any time in a simple outpatient procedure. BIONs are inert and biocompatible, so may be left in place indefinitely whether or not they are being used by the patient. BIONs have been used successfully for several years in clinical trials of therapeutic stimulation to prevent and reverse disuse atrophy [2].



**Figure 1:** BION1 implant now in clinical trials

In order to reanimate a paralyzed limb by FES, we anticipate implanting at least one BION into each paralyzed muscle. It would be convenient if these same modules could serve as sensors. As discussed below, the physical dimensions and packaging methods severely constrain the size, power consumption, and transduction methods that are feasible.

Methods to telemeter information on demand from similar injectable modules have been developed for RFID transponders used to identify animals [3]. One attractive method is to create a reflected subcarrier on the primary power carrier transmitted to each implant by the external coil. This permits all devices to continue to receive power while each device is sending its data out, an important consideration in systems that may require both high stimulus power and many sensory channels. A phase-modulated subcarrier can be created by shorting

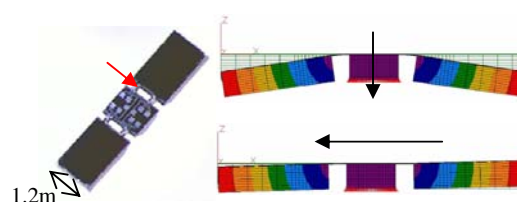
one or the other of the full-wave rectifiers on every other carrier cycle. This method has two disadvantages, however. The first is that the subcarrier is very weak, requiring sophisticated filtering to detect it reliably in the external circuitry. The second is that the outward data rate is quite low. For the 480 kHz carrier frequency that we have selected for the BION2 system, inward command data can be transmitted at 120kb/s (4 carrier cycles per bit). Outward data transmission requires 8 cycles of the 240kHz subcarrier per bit for reliable detection of phase, resulting in a rate of 30kb/s (less overhead for headers, parity, etc.). This rate limitation provides an additional motivation to select sensory modalities and sampling strategies wisely.

Interestingly, the back-telemetry data rate is not dissimilar to the information transmission rate available to the intact nervous system. The equivalent data rate available from populations of proprioceptors that generate asynchronous volleys of all-or-none action potentials is surprisingly limited by the need to extract rate information by averaging Poisson-distributed spike activity. A muscle with 100 spindle primary afferents can provide estimates of muscle movement with a resolution of about 3% (5 bits) and an update rate of about 60 measurements per second. A set of 20 muscles each with 100 spindle primary and 100 secondary and 100 golgi tendon organ afferents would have an aggregate data rate of 18kb/s. The biological controller performs well at least in part because the sensitivity of the spindle afferents to length and velocity are continuously adjusted by the fusimotor system in anticipation of the movement to be sensed [4]. Thus, a “biomimetic” strategy may be desirable, in which the incoming commands (which have a much higher data rate) are used to adjust the sensitivity of the sensors and/or to select the bits to be transmitted from a digital accumulator in each module.

### 2.1 Accelerometer – Inclinometer

Gravity provides a useful orienting signal for limb position and its effects must be considered in planning muscle activation. An accelerometer with DC response can sense gravity as well as rapid perturbations that might signify collision with an external object or unstable behaviour of the FES control system. There is no direct biological equivalent to a gravity sensor in the limbs, but the brain appears to integrate information from vestibular

gravity sensors with a representation of body posture from the head to the ends of the limbs.



**Figure 2:** Two-axis DC accelerometer small enough to incorporate in BION capsule. Red arrow denotes one of four  $3\mu$  thick silicon bridges between the central platform and the flanking proof masses. Each bridge contains two piezoresistors  $\sim 300k\Omega$  each. Deflections due to vertical and horizontal acceleration (1g) shown at right.

Commercial MEMS accelerometers typically use capacitive detection of the motion of large surface-area proof masses. In order to accommodate the small, narrow package geometry and low power budget, we have used the piezoresistive properties of lightly doped silicon (see Figure 2). The bridge is powered in brief pulses to avoid heating and the resistive elements are switched dynamically into different bridge configurations to detect two axes of acceleration. Test results indicate  $\sim 1mV/g/V_{excitation}$ , with sensitivity of 0.01-0.02g over a range of  $\pm 2g$  @ DC-20Hz.

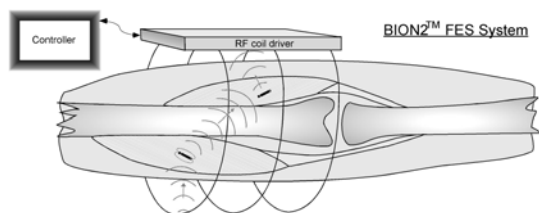
### 2.2 Bioelectric Signal Recording

Spinal-cord injured patients usually have a mix of paralyzed and voluntarily recruitable muscles. The capacitor-storage stimulating electrodes of implanted BIONs can also be used to detect bioelectric signals such as EMG even when they are precharged to the compliance voltage, as long as they are disconnected electronically from the recharging current. We have measured noise levels of  $5\mu V_{rms}$  for 0.1-10kHz.

### 2.3 Range-Finding Between Implants

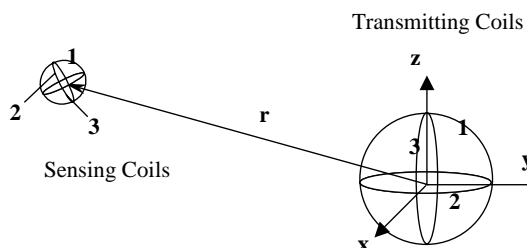
Each BION can be commanded in turn to emit a signal that other BIONs in the vicinity can detect and quantify. A brief pulse of current ( $\sim 20\mu s$ ) at high intensity ( $\sim 10mA$ ) creates a substantial electrical field that propagates through the surrounding volume-conductive tissues without producing much stimulating effect. The strength of the signal coupled between the dipole emitter and the dipole receiver tends to decrease with distance cubed and the cosine of the angle between them in a uniform, volume conductor for distances much greater than the dipole spacing. However, a

limb segment is a heterogeneous, anisotropic and delimited volume conductor, which causes the stimulus artifact to be larger at longer distances. Tests underway suggest that reasonable signal to noise ratio can be obtained over distances >15cm. It will be necessary to sample the signal just before and after the expected artifact to subtract any baseline deflection caused by background EMG, which tends to have a lower frequency content (<3kHz).



**Figure 3:** Distance between BIONs varies systematically with length changes in the muscles in which they are implanted as the joint angles change. A BIONic muscle spindle can be created by commanding one implant to emit a signal whose recorded amplitude is measured and telemetered-out by nearby implants.

## 2.4 External Reference Frame



**Figure 4:** Orthogonal transmitting coils mounted on the wheelchair can each be turned on briefly to create an RF magnetic field whose strength can be detected by the similarly tuned power-receiving coils of various implants.

RF-powered BIONs are particularly suitable for reanimating the upper extremities of spinal cord injury patients with quadriplegia. Most such patients will be seated in a wheelchair when operating such an FES system. The wheelchair frame affords convenient orthogonal surfaces on which to affix RF transmission coils similar to those that would be worn on the arm to power the implants. When the power coil is turned off, the receiving coil of each implant can be used to measure the much weaker strength of the local fields created by the wheelchair coils, which depends on the distance and relative orientation between the coils, as shown in Figure 4. We have developed closed-

form solutions to compute body posture from small numbers of such sensors, although in practice it is likely that the systems will be calibrated empirically.

## 3 Discussion and Conclusion

We are just starting the formal analysis of different combinations of sensing modalities, orientations and positions in the limb. The information so derived is likely to be over-complete and noisy and the solutions complexly constrained by anatomy and kinetics. As expected, we have found that Kalman filtering is effective in reducing the effects of noise and optimizing the accuracy of the posture estimates. One important difference between *in vitro* and *in vivo* conditions is that many limb muscles are pinnate, so that their fascicles (and the embedded BIONs) change angles as the muscles change length. If explicit representations of body posture in joint or segment angle coordinates are required, then it seems likely that these will have to be extracted by empirically calibrated algorithms. It is also possible, however, that their signals can contribute directly to motor control via trained neural networks. Our immediate task is to be sure that the computational problem is well-posed (i.e. over- rather than under-specified) for the set of sensors actually available.

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