SENSORY AUGMENTATION FOR ENHANCED CONTROL OF FNS GRASP RESTORATION SYSTEMS

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ABSTRACT

This paper describes feedback algorithms for a single electrode sensory augmentation system that provides quadriplegic individuals who use grasp restoration neuroprostheses with cognitive feedback about stimulator function and either grasp force or the output of the user generated command controller. The sensory system is based on electrical stimulation of the spinal injured individual's intact skin sense, and can be implemented using an implanted subdermally placed electrode to form a highly cosmetic system.

INTRODUCTION

Electrical stimulation of the paralyzed muscles of the forearm is being used to restore grasp function in spinal injured individuals who retain C5 and C6 level function (Peckham et al., 1980a,b). With these systems, control of the position of the thumb and forefingers, and graded regulation of the grasp strength is usually derived from an analogue signal that the user generates through voluntary shoulder movements (Buckett et al. 1980).

Supplemental feedback can be used to lessen the user's dependence on direct visualization of the hand for feedback control of grasp function. Among the information that can be furnished using the supplemental sensory system is stimulator status; contact and grasp force derived from an artificial sensor worn on the thumb; and the output of the user's command controller.

Feedback of grasp force is helpful, because the relation between the command level that the user specifies (which determines the muscle stimulation parameters) and the resultant contractile forces developed by the muscles, is non-linear and sometimes varies with time. Factors responsible for the variability between the stimulation parameters and the muscle responses are muscle fatigue, variations in the effectiveness of the excitation coupling between the muscle electrodes and the muscle tissue, and the length-tension properties inherent in the physiology of muscle contraction.

Incorporation of grasp force as a component of the sensory feedback system is intended for use mainly by C5 patients who, because of the level of their spinal injury, lack all tactile sensibility in their fingers. Many C6 patients, in contrast, retain some tactile sensibility over the surface of their thumb which might preclude the need for supplemental force information. For those C6 patients the output of the shoulder position command controller would probably more useful information for the feedback system to provide.

Feedback of the command signal can help the user compensate for inherent deficiencies of the method of attachment of the shoulder position transducer which allow its output to be affected by inadvertent postural changes of the user's upper body.

The Machine Status aspect of the feedback systems allows the user to know the status of the stimulator hardware with regard to its different operational modes and control cycles and is essential for the user to be able to control his hand function. The electrocutaneous based feedback systems replace a previously utilized system that was based on auditory cues which were sometimes embarrassing for the user and, in noisy environments, were ineffective.

The single electrode sensory system provides machine status information and a 5 level frequency code for feedback of the command signal that the patient generates to achieve proportional control of the grasp. Alternatively, the 5 level frequency code can be used to provide feedback of grasp force. The final aspect of the supplemental feedback that is communicated to both C5 and C6 users of the FNS hand systems provides information about MACHINE STATUS. This consists of a variety of electrocutaneously presented messages that assist the user in operating his hand system such as switching between PALMAR and LATERAL prehension modes, and in returning to the state of "ACTIVE CONTROL" after having utilized the system "LOCK GRASP" function.

This paper focuses on the coding algorithms and details of the electrocutaneous display used for the sensory feedback aspects of the FNS hand systems under development at Case Western Reserve University.

METHODS

Electrocutaneous Display

Electrodes- The sensory feedback system utilizes an electrocutaneous display consisting of a subdermally placed electrode that provides more comfortable and more consistent tactile sensations than are usually possible with surface applied stimulation.

Two types of implantable monopolar electrodes have been tried. They include those made of coiled stainless steel wire, and others made from "button" shaped platinum-iridium disks that are welded to flexible stainless steel leads. The former type electrode, which is similar to that developed by Caldwell and Reswick (1975), has the advantage of being able to be installed using percutaneous techniques, and, therefore, is suitable for percutaneous FNS systems. The second type of subdermal electrode has a molded Silicon rubber backing on one side to provide electrical insulation to one side of the metal disk and to provide means of attachment to the underside of the skin via sutures. The disk type of subdermal electrode must be installed surgically and is intended for use with wholly implanted stimulation hardware. The disk electrode for cutaneous stimulation is identical to the "epimysial electrode" being used for muscle stimulation in FNS systems (Grandjean and Mortimer, 1986).

Location of Sensory Electrodes- A requirement in locating the electrocutaneous display is to select a region that has intact skin sensibility. A suitable and convenient location for both percutaneous and totally implanted disk type subdermal electrodes is the region of the upper chest (C5 sensory dermatome) as depicted in Figure 1.

Indifferent Electrode- Regardless of whether a coiled wire or disk subdermal electrode is employed, each is utilized in a monopolar configuration in conjunction with a remote common indifferent anodal electrode to reduce the number of lead wires needed for the electrocutaneous display. For the percutaneous sensory system, a large remote conductive pad (41mm x 88mm) is placed on the skin surface to provide an indifferent electrode. In the case of the totally implanted sensory system, a portion of the metal package of the implanted stimulator serves as the indifferent electrode.

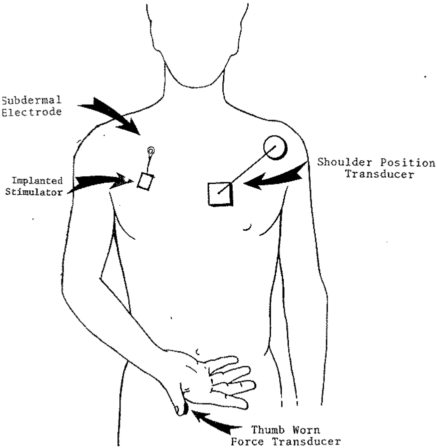

FIGURE 1

Depicting single electrode sensory system for feedback of shoulder position controller output or grasp force. One output channel from a multichannel implanted stimulator is utilized for sensory feedback. Seven additional stimulator channels (not shown) are used for muscle activation in this FNS hand system.

Stimulus Waveform Parameters- Biphasic capacitively coupled constant current pulses are employed to prevent any net accumulation of charges at the tissue interface. In addition, to prevent corrosion of the implanted electrodes, the stimulus waveform is designed to be unsymetric. Each stimulus pulse begins with a high amplitude cathodic phase of 50 us duration followed by a lower amplitude but longer duration anodic phase.

DESCRIPTION OF SENSORY SYSTEM

Overview of FNS Hand System Control Algorithms

Patients generally control their FNS hand prosthesis system by means of a chest mounted push button switch, which serves mainly to turn the system ON and OFF, and through signals derived from a two-axis proportional joystick transducer that monitors voluntary movements of the contralateral shoulder. To control the extent of hand opening and the grasp strength developed during prehension, patients use shoulder motion along the axis of protraction-retraction. Several other system functions are controlled using logical signals that the user generates by making rapid vertical shoulder movements.

Functions of the FNS system that are user selectable include a choice of either PALMAR or LATERAL hand grasp modes; the capability to specify any arbitrary position of shoulder rotation to be the "ZERO" or start position of the shoulder controller command movements; and the ability to latch or "LOCK" the hand grasp at any desired level of force.

A flow chart that summarizes the operator control algorithms for the FNS hand system is shown in Figure 2.

Each informational component of the sensory system was developed to assist users of FNS hand systems in performing a different step of the system control algorithms. The specific roles of each aspect of the sensory system in facilitating hand control are described below.

Selection of the Grasp Mode - The FNS system is in an IDLE state at the beginning of the "start-up" procedure, and there is no activity in the sensory display. The user depresses a switch mounted alongside the body of the shoulder position transducer to cause the system to enter the SELECT GRASP state. During this state the user maintains the chest switch in the depressed condition, causing the FNS system to "toggle" every two seconds between the PALMAR GRASP mode and the LATERAL GRASP mode. The alternation between the two modes of grasp during the SELECT GRASP state is signaled to the user by activating the sensory electrode at a low frequency (7Hz) to indicate palmar grasp and at a high frequency (30Hz) to indicate lateral grasp. The user releases the chest switch to select which ever grasp mode was most recently displayed (Figure 2).

Selection of the Zero Command Position - As soon as the chest switch is released, a timed interval of 3 seconds duration commences. During this period the user must move his shoulder to the position that will correspond to the ZERO or start position of the command range. At the precise conclusion of the 3 seconds the FNS system automatically accepts the then present shoulder position as the ZERO position for the command range. In general, the control algorithm is designed so that the user's full command range corresponds to only about 50% of his total possible protraction-retraction excursion. This arrangement eliminates the need for the user to produce large changes in shoulder position which can be fatiguing and can interfere with postural

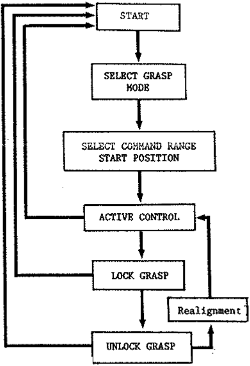

FIGURE 2

Schematic of machine states for FNS hand system control

stability while seated in a wheel chair. The user may respecify the shoulder position that corresponds to the ZERO position of the command range during each start up procedure. Such action may be desired when the user must make a gross change in posture to grasp an object that is unusually far from his body or is overhead.

During selection of the ZERO POINT, there is a risk that the user will select a shoulder position that is too protracted, and since the gain of the shoulder movement transducer remains constant, it wouldn't be possible for the user to produce the upper limits of the command range even when his shoulder is fully protracted. To preclude this possibility, the sensory system provides feedback about the absolute position of the shoulder during the timed interval for specification of the ZERO POINT as follows: Each of the five different frequency levels for the feedback stimulation is used to code for 1/5 of the range of shoulder motion. The lowest and highest frequency levels are 4 and 55 Hz respectively, and the 3 intermediate levels are pre-selected for each user in a custom manner to ensure optimal discriminability. At any given moment the sensory electrode is driven at a frequency level that corresponds to the instantaneous position of the shoulder. During specification of the ZERO POINT, the user can be assured that the full command range will be available by ascertaining that the ZERO POINT selection is made only when the sensory feedback signal is either at the 1st, 2nd or 3rd lowest frequency levels.

A confirmation of the shoulder position that the FNS system accepts as the ZERO POINT is also provided. This is accomplished by briefly increasing the subjective intensity of the skin stimulation at the frequency that was present at the time that the ZERO POINT selection period expired. The high intensity signal than ceases, and activity shifts to the 1st frequency level which then corresponds to the position of the shoulder at the beginning of the command range. Following this, the remaining four frequency levels are automatically remapped relative to the absolute position of the shoulder so that the five frequencies represent the full command range. (As explained previously, the command range is usually established to be about 50% of the user's possible range of shoulder movement). At this point, the user proceeds to the state of ACTIVE CONTROL described below.

<u>Active Control</u> - During the state of ACTIVE CONTROL, voluntary shoulder movement in the direction of increased protraction increases the command level and causes the hand to begin closing. The proportional command signal as determined by the position of the shoulder is continuously displayed to the user by activating the sensory electrode at one of the five stimulus frequencies in a manner proportional to the output of the shoulder position transducer.

Information about the strength of the grasp can be furnished by the FNS sensory system as an alternative to providing feedback about the command controller output, whenever the user is in the state of voluntary active control and is engaged in grasping activities. In this case, the grasp force information would be coded using the paradigm of five discreet frequency levels.

<u>Locking and Unlocking the Grasp</u> - Another aspect of machine status that is displayed to the FNS system user concerns initiation of the LOCK GRASP state and the user's subsequent task of "UNLOCKING" the grasp and regaining

voluntary proportional control. LOCK GRASP refers to a condition during which the user can disengage the shoulder position controller while maintaining the muscle stimulation parameters according to any arbitrary level of command. This is useful when an object is held for an extended period since the user can maintain the grasp at a fixed strength while not having to devote attention to its control.

To achieve the LOCK GRASP state, the user raises his shoulder rapidly at the extent of protraction, and, hence, level of grasp force that is desired. After the LOCK GRASP state is entered, the feedback signal is automatically discontinued to keep the skin from becoming excessively accommodated and to serve as a message confirming that the LOCK GRASP state has been entered.

To initiate the UNLOCK procedure, the user again makes a rapid vertical shoulder movement. Unlocking the grasp can present some difficulty, however, since the user's shoulder should be returned to the same position that it was in when the LOCK GRASP state was entered. This is necessary to avoid an abrupt change in the level of grasp force upon the resumption of voluntary control.

To assist the user in finding the realignment position for unlocking the grasp, a REALIGNMENT REVIEW SIGNAL is provided via the electrocutaneous display. In response to the initiation of the UNLOCK procedure, the sensory electrode is activated for 1 sec at the frequency corresponding to the position that the shoulder was in when the LOCK GRASP state was last entered. The user then moves his shoulder to the position corresponding to the realignment review signal. The user must maintain the realignment position for at least 0.5 s after which the UNLOCK task is automatically completed, and the FNS system returns to the state of ACTIVE CONTROL. Failure to maintain the realignment position for the 0.5 s interval results in a repeat of the realignment review signal.

Confirmation of the successful transition from the UNLOCK procedure to voluntary ACTIVE CONTROL is evident to the user by the return of the frequency dependence of the sensory stimulation on the output of the shoulder position controller.

System Turn-Off- A final aspect of the feedback information provided by the sensory system comes into play when the user switches the FNS system OFF. The user does this by depressing the chest mounted switch, and the sensory system immediately provides an acknowledgement of that action by alternately activating the sensory electrode at 10 Hz for 0.2 seconds and at 55 Hz for 0.2 seconds. The rapid alternation from low to high frequency activity has a unique "warbling" quality which the user can not confuse with previous signals displayed via the sensory electrode. The FNS system and the sensory display then turn off after a programmed delay of 4 seconds. The purpose of this delay is to give the user a few seconds to put down a grasped object in the event that he inadvertently switched the FNS system OFF.

Stimulator Hardware

The single electrode sensory system was first developed for use by a C6 quadriplegic patient who has sufficiently good tactile sensibility over the surface of his thumb, that he does not require artificial feedback of grasp force, and, therefore his system provides command controller output as a major component of the feedback information. This patient's sensory substitution system utilizes a monopolar, subcutaneous platinum-iridium electrode located in the region of his upper chest (as described in METHODS) to induce cutaneous sensations. The sensory electrode is driven by a multi-channel implanted stimulator. The stimulator provides seven independent channels for muscle stimulation to produce coordinated hand function in addition to a single sensory feedback channel. Control and power for the implanted stimulator is derived from a transcutaneous radio frequency coupling. Further information regarding the multichannel implantable stimulator may be obtained by referring to Smith et al., 1987.

Where a percutaneous FNS system is to be used, the percutaneous coiled wire subdermal electrode (previously described) would be utilized for the electrocutaneous display. Presently available stimulator hardware for such a system consists of a portable microprocessor based device that can drive up to 16 channels of output independently (Buckett et al., 1985).

DISCUSSION

The grasp force and command signal feedback functions of the electrocutaneous sensory system described in this paper are novel for the FNS systems, however, some machine status feedback functions were previously served using a system of auditory cues that provided the user with verification that the FNS system had acknowledged or executed various control commands. While the auditory feedback scheme has been clinically deployed at in the Case Western program for many years, users have consistently identified several deficiencies: The codes were sometimes difficult to learn or to remember; the auditory cues were sometimes impossible to attend to in noisy environments, and in certain social settings such as dining, they were a source of embarrassment. The electrocutaneous sensory feedback system has the inherent advantage that it is totally private. This is an important advance toward ensuring user acceptance of the FNS hand systems.

There are several reasons why grasp force feedback, and the anticipated enhanced ability of the users to regulate grasp force are important, aside from that of ensuring that grasped objects are not dropped. For example, it is beneficial for users to avoid using more force then is necessary for a given task in order to forestall muscle fatigue, and to prevent delicate objects from being crushed. In the case of objects that have rough or sharp edges, precise control of grip strength may be necessary to prevent damage to the fingers or hand.

The alternative application for the frequency coded sensory feedback channel (to provide information about the output of the command signal) should enable the FNS system users to produce more accurate and more precise commands. The effectiveness of providing this feedback information was suggested from the results of prior studies of patients' abilities to track a visually presented randomly moving target with movements of their shoulder in the presence and absence of electrocutaneous sensory feedback (Riso and Ignagni, 1985).

Where an individual will be using a percutaneous FNS system, one has the option of providing either the single electrode sensory feedback code that is described in this paper, or alternatively, a multi-electrode sensory feedback system can be employed. Implementation of such a system is possible because of the availability of up to 16 output channels with the most recently developed portable stimulators for percutaneous FNS systems. A multi-electrode sensory system has been planned and is intended to benefit those individuals who do not possess good tactile sensitivity in their fingers.

The multi-electrode sensory system uses five subdermal electrodes spaced about 35 mm apart on the upper chest skin (Riso et al., 1987). This spatial electrode array is used for spatial position encoding of the shoulder controller output signal. By modulating the stimulation frequency of whichever sensory electrode of the array that is active, it is possible to superimpose frequency encoded information about the force of the grasp, and thus provide both command signal and grasp force feedback simultaneously.

Successful deployment of sensory feedback systems with a grasp force component will depend on the future availability of highly cosmetic and reliable sensors that can transduce the force at the fingers. Thin, conformable, light weight force sensors that can be worn on the fingers are needed, and at least one laboratory is working to develop devices to satisfy this need (Neuman et al., 1987).

Efforts have been initiated to obtain confirmation of the efficacy of the current sensory feedback system under objective and carefully controlled laboratory tests, and it will be our future goal to develop means of assessing the usefulness of the sensory feedback system for the FNS system users as they utilize their hand systems in their daily activities outside the laboratory.

SUMMARY AND CONCLUSIONS

A sensory system for use with FNS grasp restoration neuroprostheses was described. The sensory system utilizes a frequency encoded electrocutaneous communication channel formed from a single electrode to provide FNS system users with feedback of the machine status of their stimulator hardware, and either the output of their self-generated command signal or the level of grasp force developed during prehension tasks. The sensory system that has been described has been implemented for one C6 quadriplegic individual using a subdermally placed cutaneous electrode in conjunction with an implanted multichannel stimulator. These innovative aspects of the electrocutaneous display are expected to provide enhanced system reliability and superior clarity, comfort and consistency of sensation then would be possible using surface applied electrocutaneous stimulation. The new feedback system has been demonstrated to successfully replace a previously used feedback communications channel that was based on auditory cues.

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