

CHAPTER 5

Sensory feedback for upper limb prostheses

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Abstract: In this chapter, we discuss the neurophysiological basis of how to provide sensory feedback to users with an upper limb prosthesis and discuss some of the theoretical issues that need to be considered when directly stimulating neurons in the somatosensory system. We focus on technologies that are currently available and discuss approaches that are most likely to succeed in providing natural perception from the artificial hand to the user. First, we discuss the advantages and disadvantages of providing feedback by stimulating directly the remaining afferents that originally innervated the arm and hand. In particular, we pay close attention to the normal functional roles that the peripheral afferents play in perception. What are the consequences and implications of stimulating these afferents? We then discuss whether it is reasonable to stimulate neurons in the ascending pathways that carry the information from the afferents to the cortex or directly in neurons in the primary somatosensory cortex. We show that for some modalities there are advantages for stimulating in the spinal cord, while for others it is advantageous to stimulate directly in the somatosensory cortex. Finally, we discuss results from a current experiment in which we used electrical stimuli in primary somatosensory cortex to restore the percept of the intensity of a mechanical probe indented into the hand. The results suggest that the simple percept of stimulus intensity can be provided to the animal from a single finger using four electrodes. We propose that significantly more electrodes will be needed to reproduce more complex aspects of tactile perception.

Keywords: Sensory feedback; electrical stimulation; Somatosensory organization; Neural code.

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Introduction

Often science fiction paves the way toward innovation and discovery. An example is the prosthetic limb Luke Skywalker uses in the movie “The Empire Strikes Back”. In the movie, Luke not only moves his prosthetic hand with the dexterity and strength of his original but also

receives robust sensory information that allows him to effortlessly grasp and manipulate objects (including his light saber) and perceive sensory inputs related to pain. While current technologies are far from achieving such lofty goals, we are starting to realize how to turn this fantasy into reality. Thus far, the most exciting advances in prosthesis research have come in the area of motor control (e.g., [Velliste et al., 2008](#)). These studies demonstrate that it is highly feasible for animals to accurately control movements not only of a prosthetic arm but also of the individual fingers of a prosthetic hand ([Acharya et al., 2008](#)). In these motor studies, single unit responses or local field potentials from populations of individual neurons, or the recordings from ECoG recordings from chronically implanted neurointerface chips, or arrays of microelectrodes located in motor cortex are decoded to determine the desired movement of the user. These decoded signals are then used to drive electrical motors that move the prosthesis. The current challenge in this area of prosthesis research is to determine how to use these cortical signals to give users fine coordinated movements of the prosthetic hand.

However, dexterous control of the prosthesis is only half of what is needed to achieve the ideal prosthesis. What is also needed is high-quality sensory feedback that will enable users to know where their hand and arm is in space and to let them feel what the prosthetic hand is touching. It is only when both flexible motor control and sensory feedback are integrated will the upper limb prosthesis be considered a complete success. In this chapter, we focus on what is needed to provide robust sensory feedback to prosthetic arm users. While current methods of providing feedback are relatively crude, it is clear that they demonstrate the fundamental issues that need to be solved. Currently, three approaches are used to provide feedback. All three approaches assume that there is a fully instrumented hand with sensors that mimic or are capable of capturing information that was encoded by the original receptors in the skin. This information can then be processed to drive the appropriate sensory substitution device.

The first approach is targeted reinnervation ([Kuiken et al., 2007](#)), where the afferent fibers that once came from the hand are moved to target tissues in the upper chest. After the skin has become reinnervated, touching the skin evokes the perception that the missing hand is being touched. To produce percepts that are useful to the user, the skin on the chest can then be stimulated using mechanical stimulators that target orphaned afferent fibers. While the approach has been successful in giving prosthesis users some feedback, it has limited potential since there is only partial reinnervation of the skin and as such the information that can be delivered to the user is restricted to the afferent fibers that sparsely activate random patches of skin that map on to skin that use to be on the hand. The second approach is to use sensory substitution methods whereby signals from the prosthesis are used to activate a sensory substitution device that the user then learns to interpret as a sensory signal related to the prosthesis. For example, one such device stretches the intact skin somewhere else on the body back and forth using skin contactors that rotate on the forearm. Changes in hand position of the prosthetic are encoded as changes in the amount that the skin is stretched by the device. Another example would be a set of vibrators located on the forearm or back. Activating different combinations of vibrators are then discriminated as different components of the sensory input (see [Jones, 2011](#)). This approach is limited by the number of independent signals that can be processed and perceived by user.

The third kind of sensory feedback, which holds the most promise and is the focus of this chapter, is to stimulate directly either the afferent fibers in the arm or spinal cord or neurons in the somatosensory cortex. While current technologies use electrical stimulation, it is highly likely that in the near future, neurons will be stimulated using optical methods. The reason why this approach has the greatest potential for giving users natural sensory feedback is because it has an unlimited potential to stimulate large populations of neurons and it takes advantage of the inherent modality specificity of the underlying neurons.

Below we first describe the roles and functions of the sensory afferents that innervate the hand with an eye toward determining how to restore these sensory functions to the prosthesis user. We then discuss a theoretical framework for providing sensory feedback to users and finish with a discussion showing the results from current experiments in our lab in which we use direct stimulation of neurons in the somatosensory cortex to give animals the perception of a mechanical probe being indented into the skin at different intensities.

Functional roles of the peripheral afferents for feedback for action and perception

Sensory feedback from the receptors in the arm and hand play two important roles. The first is to provide feedback for producing controlled action or movements of the hand and arm and the second is to provide inputs that give users sensory experience. The functions of sensory feedback for action

and perception are overlapping since under normal circumstances we need to move our hands to manipulate and explore objects. However, it is useful to conceptually separate these functions to see what sensory information is needed to restore specific functions.

Table 1 gives a summary of the 13 kinds of afferents that innervate the hand. It can be seen from this table that the nervous system solves the problem of sensing its environment by having an initial set of afferent fibers that are selectively sensitive to different features of external stimuli and to different components of the internal state of the hand. An important principle that can be taken from this table is that the somatosensory system is not a single system but instead is composed of multiple parallel processing streams with each stream originating from a distributed set of specialized receptors and terminating in parallel in central and subcortical regions in the brain. Reproducing the information from these parallel input streams, each of which is receiving

Table 1. Peripheral receptor types in the primate hand (glabrous skin only for cutaneous mechanoreceptors)

Receptor	Fiber group	Receptors respond to	Function
<i>Cutaneous, low-threshold mechanoreceptors</i>			
Merkel (SA1)	A β	Steady deformation and motion	Local form (e.g., Braille) texture (roughness, hardness, etc.)
Ruffini (SA2)	A β	Skin stretch	Skin stretch, digit/hand conformation
Meissner (RA)	A β	Skin movement (glabrous skin only)	Light touch, local movement, slip (for grip control)
Pacinian (PC)	A β	High-frequency vibration	Distant events (hand-held tools)
<i>Proprioceptors</i>			
Muscle spindle (Ia)	I	Muscle length and velocity	Position, movement
Golgi tendon organ (Ib)	I	Muscle force	Muscle force
Muscle spindle (II)	II	Muscle length	Position?
Joint	II	Joint angle, movement	Unclear (sensitive to extreme joint angles)
<i>Thermoreceptors</i>			
Cold	A δ	Drop in skin temperature	Cold (temperature of object relative to skin temperature)
Warm	C	Warmth	Warmth
<i>Nociceptors</i>			
Small myelinated	A δ	Noxious stimuli	Sharp, pricking pain
Unmyelinated	C	Noxious stimuli	Dull, burning pain
<i>Itch</i>	C	Pruritic stimuli	Itch receptors

information from thousands of afferent fibers, using electrical or optical stimulation methods is not a simple problem.

Sensory feedback for action is necessary since it gives users the feedback required to control the movements and forces needed to grasp and manipulate objects. In this role, the proprioceptive feedback gives the user information about the positions, movements, and forces of the limb, hand, and fingers. The afferent fibers that provide the feedback for action are the four kinds of proprioceptive afferents that provide information about the positions, velocities, and forces of the arm and hand. As shown in the table, information about muscle force is carried by the Golgi tendon organs, which are located in the tendons of the muscles. These receptors are in series with the muscle fibers and along with an efferent copy of the motor command signal that is generated in the cortex, is the basis for the perception of muscle force. Information about muscle force plays an important role in everyday life. For example, you need to know how heavy objects are to smoothly grasp and lift them. The sense of force could be given to the user with a sensory substitution device or by stimulating the afferent fibers directly in the remaining nerve or spinal cord. Stimulating directly in the cortex is currently not an option since the central projections of these afferent fibers is not known.

The second kind of proprioceptive afferents are joint afferents which include a variety of afferent types that end in free nerve endings and paciniform corpuscles located in the joint capsules. Originally, it was thought that these afferents were responsible for conveying information about joint angle; however, this was ruled out because neurophysiological recordings showed that these afferents respond only at the extremes of joint flexion and extension and thus gave poor representations of precise joint angle. It is currently thought that these afferents function as limit detectors and give users a perception of when joints are extended to their extremes. These signals are useful but not essential in everyday

function since humans with joint replacement surgery maintain normal functionality. Thus, replacing the function of these afferents appears to be minimally important and can be built directly into the motors.

The third and fourth kinds of proprioceptive afferents receive their inputs from the two kinds of muscle spindle afferents located in the intrafusal muscles. While these afferents are clearly needed for controlling muscle length, their role in perception is less clear since they do not seem to carry accurate measurements of joint angle and velocity (Dimitriou and Edin, 2008). However, there is convincing evidence that some aspect of joint angle is carried by these afferent types. One demonstration is the Pinocchio effect in which subjects are asked to place their finger on their nose. The belly of the muscle is then vibrated, which activates the muscle spindle afferents which in turn evokes the perception that the joint angle of the arm is increasing. Since the finger is still in contact with the nose, subjects perceive that their nose must be growing! However, it is doubtful that the signals provided by these afferents are sufficient to convey fine joint angle. If joint angle is not carried by these muscle spindle afferents then the question arises as to which afferents convey information about joint angle.

The answer to this question appears to come from the cutaneous afferents that innervate the skin. Edin and Johansson (1995) have provided strong evidence that the slowly adapting type 2 (SA2) afferents in the skin contribute strongly to the sense of joint angle and they propose that the pattern of neural activity across the population of SA2 afferents conveys information about fine joint movements to the central nervous system (Dimitriou and Edin, 2008; Edin and Johansson, 1995). Given our current understanding of how joint angle is coded and represented in the peripheral afferents, it appears as if separate populations of SA2 afferent and muscle spindle afferents must be stimulated in a coordinated fashion to produce veridical percepts of joint angle. This approach is theoretically possible,

however, we do not currently have a sufficient understanding of how joint angle is coded in the peripheral afferents to produce the necessary pattern of stimulation. As described later, a more reasonable candidate is to directly stimulate neurons in cortex where the integration between the different afferent types encoding joint angle has already occurred.

Besides the SA2 afferents there are three other kinds of peripheral mechanoreceptive afferents that innervate the skin. The Pacinian (PC) afferents have very large receptive fields and innervate the skin sparsely. These afferents are responsible for conveying information about vibration and play a key role in conveying information about events distant from the hand—as when we use tools. In intact humans, as exemplified by a blind person using a cane, these afferents in combination with inputs from the proprioceptive afferents convey information about the form and texture of objects. With the vibratory sense, a blind person can construct an internal representation of his or her environment based solely on inputs that they receive through the cane. This suggests that providing prosthesis users with the sense of vibration through the PC system is a viable way to give sensory feedback about their environment and is critically important when the prosthesis is used to manipulate tools. Providing vibratory input requires that the outputs of accelerometers imbedded in the prosthesis are decoded and turned into electrical signals that mimic the temporal pattern of what a PC afferent would have experienced under the same circumstances. That is, to be interpreted properly by the brain, the signals must carry the same temporal information that the central nervous system uses when extracting information about textures with tools (Yoshioka et al., 2007). Although we still do not understand how complex vibratory inputs related to generalized texture perception are represented in the PC system, this is a solvable problem.

The other two afferent types, the rapidly adapting (RA) and slowly adapting type 1 (SA1) afferents, convey information to the central nervous system about motion (RA) and two-dimensional (2D) form

and texture (SA1). The RA afferents are highly sensitive to minute movements on the skin, sense when objects begin to slip in the hand, and provide sensory feedback to the user about increasing grip force. Clearly, this afferent system is important if the prosthesis is to be used to grasp and lift objects without crushing or dropping them. Under normal circumstances, the skin is densely innervated by the RA afferents which allows for users to make rapid fine adjustments in grip force as objects slip between the fingers. Thus providing feedback to replace these functions requires that slip sensors be built into the prosthesis with the outputs decoded and used to activate the relevant motors involved in grasping the object. It is not obvious that these signals for grip control need to be fed back directly to the RA afferents since information needed for fine grip control occurs rapidly (most likely in the form of a spinal reflex) which occurs before the information about the object slipping reaches consciousness. RA afferents are also important for the perception of tactile motion and are used when the hand scans surfaces, but these functions are better recreated by stimulating neurons in the cortex. It is important to note that volitional control of the prosthesis is important and that automated grasping functions of the prosthesis could be disturbing to the user. The image that comes to mind comes is Dr Strangelove, from the movie of the same name, whose artificial hand seems to act of its own accord. In summary, providing the user with inputs from the RA system at the peripheral level may not be critically important for providing feedback for grasping.

The fourth kind of mechanoreceptive system is based on inputs from the SA1 afferents. These afferents have been shown to convey information about 2D form and texture (Hsiao and Bensmaia, 2008; Hsiao et al., 1996; Johnson et al., 2002) and play an important role in encoding mechanical intensity (Hsiao et al., 1996; Muniak et al., 2006). In combination with inputs from the proprioceptive afferents, the SA1 afferents are also critically important for coding object size and shape (Hsiao, 2008). Thus activating the SA1 system is critical for a prosthesis to be successful

since these afferents are the equivalent of the tactile visual system and convey spatial information about the distribution of stimuli on the skin to the central nervous system (Hsiao, 1998). Information about edges, roughness, or softness are normally conveyed to the central nervous system by these afferents. Effective stimulation of this spatial system requires that a large number of afferent fibers be activated to convey an effective 2D image of the spatial distribution of the patterns on the skin. While activating enough fibers to give a sense of pressure on the skin is possible, selectively activating enough peripheral SA1 afferent fibers to convey information about 2D form and texture is not realistic given our current technology. However, it is important to note that an alternative possibility described later is to stimulate neurons directly in cortex that are already coding for 2D stimulus features.

Another class of peripheral receptors are the nociceptors which are the afferents responsible for conveying information about itch or painful events that result in damage to the skin. The ability to convey pain information leaves open the potential of giving users the perception of when the prosthesis itself is in danger of being damaged. For example, if a sensor on the prosthesis “perceives” that it is about to be damaged then an electrical pulse could signal the user by activating a pain afferent. Restoring the sense of pain is not essential for a prosthetic hand to be considered a success.

The last kind of input fiber encodes the perception of temperature. These afferents provide information about both warm and cold and although potentially not critical for action, the sense of temperature plays an important role if the hand is to be used to provide affective percepts. For example, the pleasure of holding someone's hand at least partially comes about because one can sense the warmth of the receiver. Sensing temperature and stimulating the thermal afferents is probably important if the prosthesis is to feel like a natural hand.

As can be seen from the above discussion there are 13 aspects of hand function that need to be restored for a prosthesis to replace normal

sensory inputs. In addition, for each afferent type, a large population of afferents need to be simultaneously stimulated for the prosthesis to completely replace the normal hand. One possible method to reduce the dimensional explosion that is required to achieve this goal is to activate neurons further up the processing pathways where the information has already been segregated into different pathways and has been integrated to extract out selective features of the external world. In the next section, we review the ascending and central pathways that underlie tactile perception (Fig. 1).

Ascending pathways to perception

There are numerous potential places in the parallel ascending pathways that carry the inputs from the peripheral afferents to the cortex where electrical (or optical) stimulation could be performed. These include stimulating directly in the spinal cord, in the dorsal horn, dorsal column nuclei, medial lemniscus, the ventroposterior lateral nucleus (VPL) of the thalamus. Each of these sites has potential strengths and weaknesses. The major advantage is that each of these sites are organized somatotopically, with afferents carrying information about mechanoreception and proprioception ascending in the dorsal column medial-lemniscal pathway and information concerning pain and temperature ascending in the anterolateral pathway. The segregation of function along with the fibers being anatomically organized has the advantage of allowing one to specifically target afferents related to the desired body part (hand) and sensory modality (mechanoreception, proprioception, or temperature). Furthermore, stimulating in the dorsal horn (Luo et al., 2009) or ascending spinalthalamic track may be the optimal way to artificially evoke the percepts of pain and temperature since currently the central projections for these afferent fibers has not been clearly established. There is evidence that stimulating along the dorsal column pathway may be a viable approach in restoring mechanoreceptive

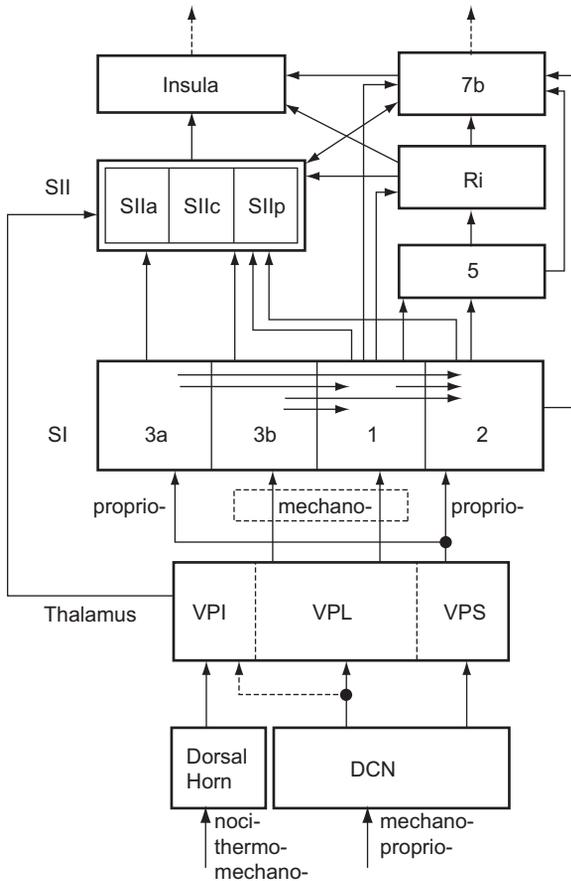


Fig. 1. Block diagram of the somatosensory pathways. DCN, dorsal column nuclei; VPI, ventroposterior inferior; VPL, ventroposterior lateral; VPS, ventroposterior superior; SI, primary somatosensory cortex; SII, second somatosensory cortex (a, anterior; c, central; p, posterior), Ri, retroinsular.

function (Gaunt et al., 2009). The major drawback in stimulating the spinal cord is that it is difficult to implant and target these structures and further, stimulating brain stem regions has the potential of creating unwanted side effects.

Primary somatosensory cortex

The next logical place to evoke somatosensory percepts is in primary somatosensory cortex. During the early part of the last century, Penfield

and Jasper found that stimulation of the postcentral gyrus in human patients evoked systematic patterns of sensations of the body as they moved the electrical stimulus to different locations on the postcentral gyrus. Using this technique, they uncovered a representation of the body, or homunculus, in primary somatosensory cortex (Penfield and Boldrey, 1937). Further experimentation with electrical brain stimulation in the sensory cortex and other areas has demonstrated that electrical stimulation in specific brain regions can convey a specific percept associated with those regions in a behavioral task. Romo et al. (1998, 2000) used rhythmic electrical stimulation at a number of different frequencies to replace the mechanical vibrations of the tactile probe (Romo et al., 1998, 2000). The electrical stimulation was performed in a specific region of cortex which has been shown to be sensitive to flutter discrimination frequencies (Carli et al., 1971). More recently, it has been shown that nonhuman primates can discriminate spatial and temporal patterns of direct stimulation of primary somatosensory cortex (Fitzsimmons et al., 2007).

Previous attempts at stimulation have not only demonstrated that the sensations of the body are closely associated with the activity of neurons in primary somatosensory cortex but also that the evoked percepts correlate closely with the modality specificity of neurons located in specific cortical columns. These results suggest that it may be possible to give patients with upper limb prostheses the natural perception from the prosthetic limb if neurons in the cortex are properly activated. The question then arises as to what it means for the cortex to be “properly activated.” As a first step in addressing this question, it must be noted that primary somatosensory cortex is composed of four distinct areas that are called areas 3a, 3b, 1, and 2. Each of these areas has been shown to (1) have a unique cytoarchitecture, (2) have a unique set of input and output projections, and (3) respond differently to somatosensory stimulation. Furthermore, studies in nonhuman primates show that selective ablations of these areas produce unique deficits in the ability

of the animals to perform tactile tasks ([Randolph and Semmes, 1974](#)). These simple findings suggest that the selective activation of neurons in each of these areas should evoke selective percepts. Thus stimulation of neurons in area 3a, which is composed of neurons that respond to movement of the joints, should produce percepts related to proprioception, stimulation of neurons in areas 3b and 1, which is composed of neurons that respond to cutaneous input, should evoke percepts related to cutaneous input, and stimulation of neurons in area 2, which contain neurons that receive both cutaneous and proprioceptive input should evoke perception of three-dimensional (3D) objects. But randomly stimulating neurons in these areas is not sufficient to produce natural percepts since each of these areas are composed of columns of neurons that are body location and modality specific. It is precisely for this reason that Romo finds that he can only evoke the percept of flutter when he selectively activates neurons in area 3b that respond to RA-like input ([Romo et al., 1998](#)).

The ultimate goal for producing natural percepts with a prosthesis is to reproduce as closely as possible the normal patterns of neural activity that are produced by the natural arm and hand. To rephrase this statement, the goal is to understand how somatosensory information from the hand is coded and represented in the cortex and to artificially produce those representations using artificial stimulation.

Using the natural underlying neural code to restore sensory function is the approach that has successfully been used in cochlear implant patients. In the cochlea, sounds are laid out along the cochlear membrane as a tonotopic representation. In these patients, a linear array of a dozen or so electrodes are inserted along the cochlea and electrical stimuli are used to selectively activate the membrane in a manner that best simulates the natural pattern of activation during speech. Cochlear implants have been a huge success in restoring hearing to a large number of patients with peripheral hearing loss. The success of the cochlear implant shows that a similar approach

of exploiting natural neural codes should be used for patients with upper limb prosthesis to restore normal hand function.

The question then arises as to what neural code(s) is used by neurons in somatosensory cortex when performing tactile tasks. As discussed earlier, the hand plays many roles in everyday life. We use our hands to perceive properties of objects such as their size, shape, and texture (smooth, rough or hard or soft) when we directly contact and explore objects with our hands. We also use inputs from our hands to explore the environment indirectly through tools that we hold in our hands. Finally, we use our hands to interact with our environment, for example, when grasping and manipulating objects. Recent studies in the Hsiao lab have shown that the neural coding mechanisms employed by touch are highly similar to the ones used by the visual system. In particular, there is now strong evidence that the orientation of a bar indented in the skin is coded by a population of orientation tuned cells in area 3b that have receptive fields consisting of oriented bands of excitation- and inhibition-like neurons in primary visual cortex ([Hsiao et al., 2002](#)). Furthermore, the representation of stimulus motion on the skin appears to be processed by populations of neurons in area 1 that respond most effectively to pattern motion rather than to component motion ([Pei et al., 2010](#)). Finally, it has been shown that neurons in area 2 and SII cortex respond to stimulus curvature in a way that is highly similar to the tuning that is observed in area V4 in the visual system ([Yau et al., 2009](#)). Together, these results suggest that form, texture, and motion are represented by neurons in primary somatosensory cortex that are highly selective to features of stimuli on the skin. These results suggest that to achieve a robust prosthesis that has true sensory feedback requires that populations of neurons in S1 cortex be selectively activated in a manner that is consistent with the natural underlying neural codes that are normally used by the somatosensory system to code for features such as motion, form, and vibration.

An advantage of stimulating neurons directly in primary somatosensory cortex is that it takes advantage of the existing cortical machinery that currently exists for extracting information about the environment. Thus one does not need to stimulate entire populations of neurons from each of the peripheral afferent types but instead all that is needed is to stimulate columns of neurons that code for a specific feature such as orientation to evoke the percept of the orientation of an indented bar. In the next section, we discuss results from experiments that we performed in somatosensory cortex to simulate the perception of mechanical intensity.

Using electrical stimulation to produce the percept of mechanical intensity

The aim of the experiment was to train a nonhuman primate (*Macaca mulatta*) to discriminate the intensity of a mechanical probe indented into

the skin on the hand. In the study, the animal sat in a chair with its hand restrained and facing upward. The stimuli consisted of a small 1-mm probe, mounted on a NorMag linear motor, that could be positioned anywhere over the animal's hand using a platen–forcer system. The animal was then trained to perform two tasks. In the first, the animal performed a two alternative forced choice (2AFC) task whereby the probe was indented into the skin during one of the two intervals. The animal's task was to report using a foot switch whether the stimulus occurred during the first or the second interval. The second task was similar to the first except that the animal was given two mechanical stimuli and was required to report whether the more intense stimulus occurred in the first or second interval. The animal was trained to perform the two tasks at several locations on its hand to ensure that it could generalize across skin locations (Fig. 2).

Once the animal learned to perform the two tasks, a Utah electrode array (UEA) from

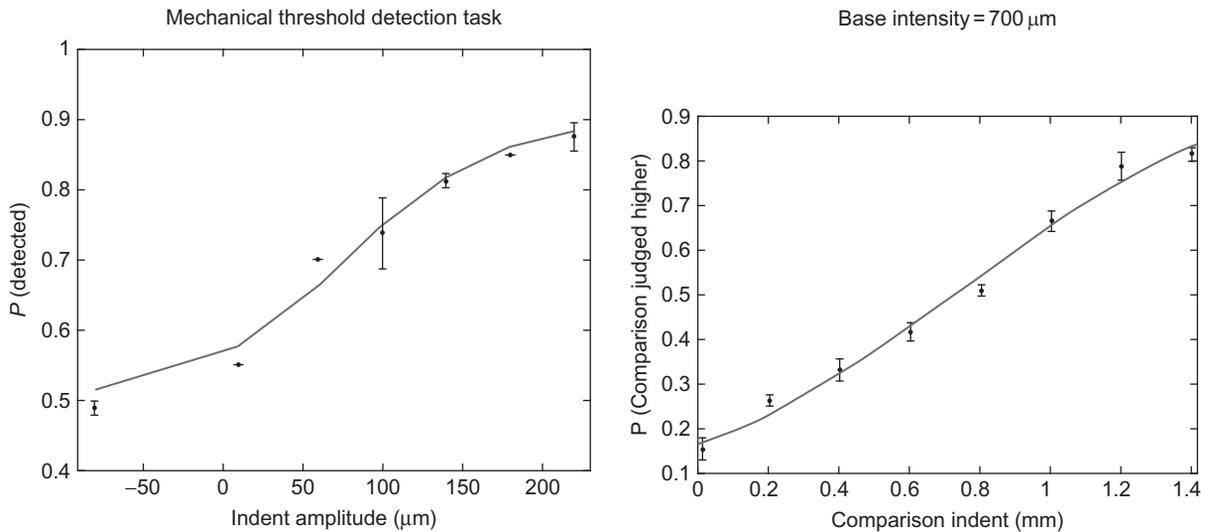


Fig. 2. Left graph. Detection of mechanical indentation of varying amplitudes around threshold. Each point represents 120 trials; error bars are based on four trials of 30 data points each. Right graph. Discrimination of mechanical indentations against a comparison amplitude of 700 μm (each data point is composed of 256 trials; error bars are based on eight experiments of 32 trials each). The indentation threshold was similar to earlier reported detection and neural thresholds in humans (Johansson and Vallbo, 1979a,b).

Blackrock Microsystems was implanted into the hand region of the somatosensory cortex and recordings were made using the Cerebus recording system. Figure 3 shows a somatotopic map of the recording locations of the 100 electrodes in the UEA. As can be seen, the array spanned the cortical map corresponding to the face and digits 1 and 2 of the animal. Because the length of the array was limited to 1.5 mm, it was unable to record from deep structures and as such the responses were restricted to a single layer of cortex in area 1. Because of the difficulty in presenting mechanical stimuli to digit 1 or the face, we chose to concentrate the experiment on digit 2.

Stimulation details

Electrical stimuli were delivered with a custom built current-regulated electrical stimulator that had the ability to stimulate different patterns simultaneously on four output channels. The stimulator could generate stepwise arbitrary current waveforms with a memory capacity of 256 steps (per channel). The output current amplitude resolution was 30 pA, with a maximum output to ± 0.98 mA. The time resolution of the output was 1 μ s; with a minimum of 3 μ s for each time-step and a maximum of 65 ms between each time-step. The stimulator was optically isolated and was driven with custom-written Matlab code.

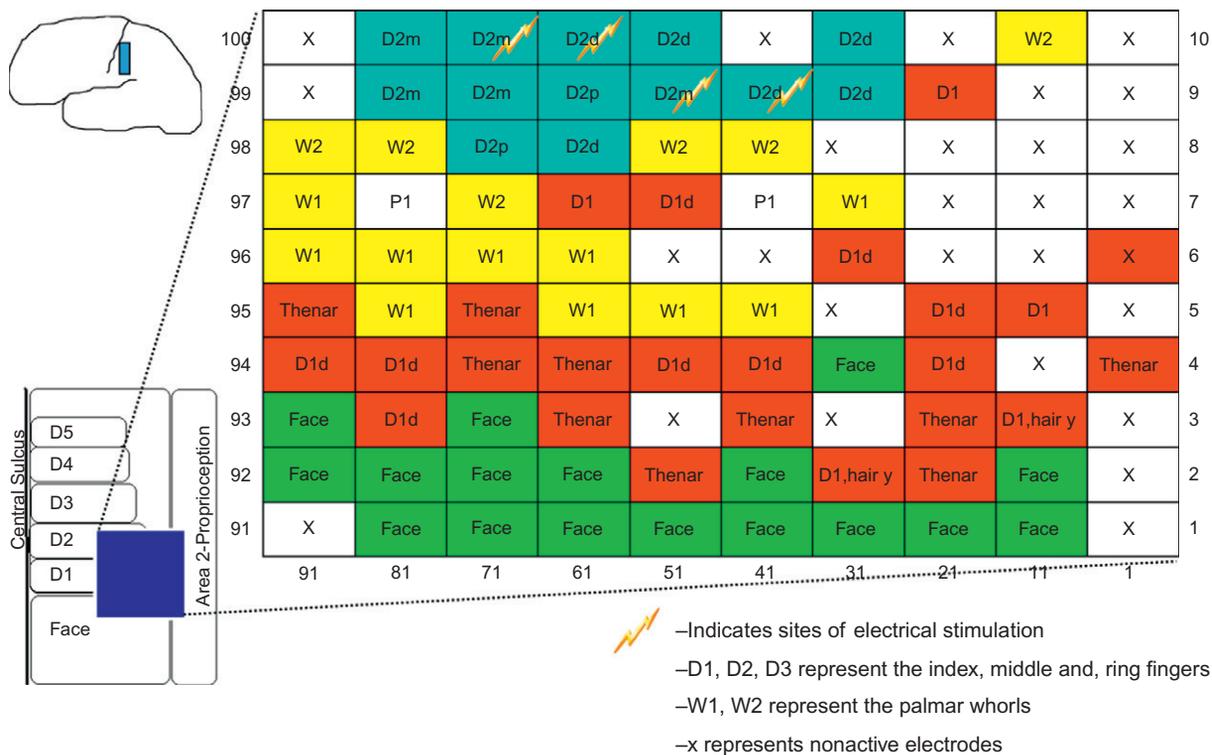


Fig. 3. Somatotopic map of the responses evoked from the Utah electrode array.

All stimulation pulses were symmetric biphasic pulses with pulse widths of 100 ms and no delay between anodic and cathodic phases; each biphasic pulse lasted for a total of 200 ms. All pulse trains were contained within a 400-ms pulse window. High-frequency stimulations (200 Hz) used 80 pulses during that 400 ms window with constant interpulse intervals. We were limited to a maximum of ~ 83 biphasic pulses based on the stimulator. Low frequency stimulation used eight pulses during the 400-ms pulse window.

Electrical substitution task

We choose four stimulation sites (electrodes) for stimulating the cortex using electrical stimuli (Fig. 3). The sites were chosen based on recordings using the mechanical stimulator that these neurons were highly rate sensitive to the intensity of the stimuli. We first determined the electrical threshold for perception. In this experiment, the monkey reported whether he perceived the electrical stimulation in the same manner as the mechanical threshold task described above (Fig. 4).

The results for the electrical detection experiment are shown in Fig. 4. In this experiment, the animal received a high-frequency (200 Hz) stimulus of bipolar electrical pulses of varying amplitude. The hypothesis behind the experiment is that increasing the current amplitude should cause a systematic spread of neurons that are activated by the stimulus and that it should be easier for the animal to detect this increase in neural activity as the current amplitude increases. The systematic increase in detection with increases in current amplitude suggests that the perceived amplitude of the stimulus also increased. That is, if the stimulus was perceived as an artificial unnatural sensation, which we call an “electrical buzz”, then we would have expected a step-like detection threshold instead of the smooth psychometric function. When a lower frequency stimulation was used, we observed that detection threshold rises more

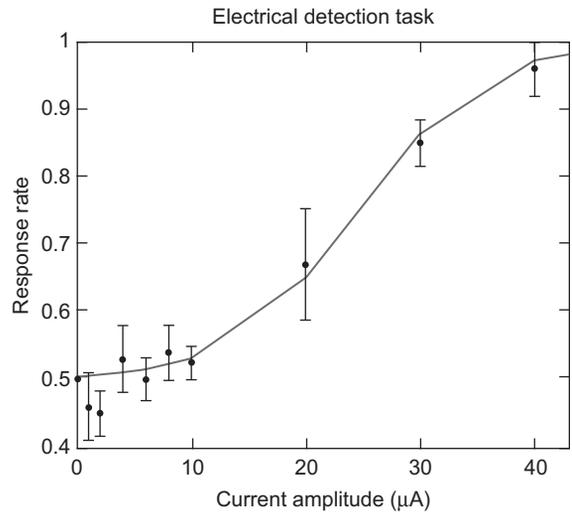


Fig. 4. Detection of a high-frequency electrical stimulus with regular interspike interval spacing.

rapidly with high frequency than with low frequency stimulation as the current amplitude increases. These data demonstrate that when giving animals a perception of stimulus intensity, a wider range of intensity values (i.e., current levels) are available when low frequencies rather than high frequencies are used as the base frequency.

Electrical/mechanical intensity discrimination

As a final set of experiments to test whether the patterns of electrical stimulation evoke natural percepts of stimulus intensity, we asked the animal to perform the mechanical intensity discrimination task with some of the comparison stimuli being a range of high-frequency electrical test stimuli. We hypothesized that the psychometric functions should be similar to the mechanical–mechanical trials if the electrical stimuli produce veridical intensity percepts and that the animal should not be able to perform the task if the percepts evoked by the two kinds of stimulation are completely different. To ensure

that the animal did not learn to make this association, we interleaved the mechanical–mechanical trials with the mechanical–electrical trials. We used the threshold value of $24\ \mu\text{A}$ from the high-frequency electrical detection task as a guide and tested current amplitude values from 0 to $160\ \mu\text{A}$ against a comparison mechanical stimulus of $200\ \mu\text{m}$ (Fig. 5). From these data, we estimate that a $200\text{-}\mu\text{m}$ mechanical indent corresponded to a current amplitude of about $55\ \mu\text{A}$.

Figure 6 shows the estimated relationship between the amplitude of the stimulation current and the perceived indentation depth. The data suggests that the relationship is not linear, which is reasonable since the current spread from a point source is not linear and one would expect that proportionally more neurons would be activated as the current level increase.

The results from these experiments clearly show that the intensity of a mechanical stimulus can be produced by increasing the intensity of the current used to drive the neurons. A confounding issue with these results is that Romo reported that increasing current in an RA column also produces the perceived increase in vibratory

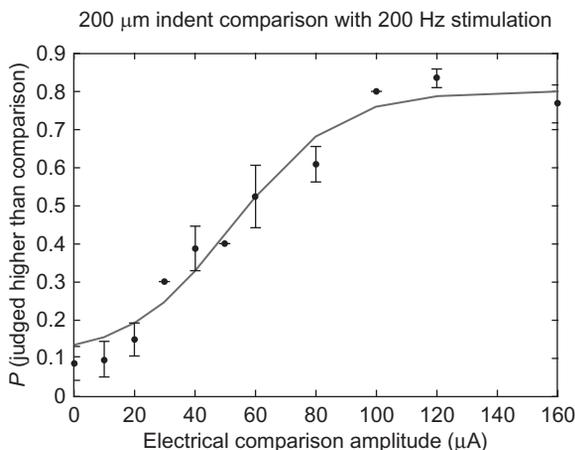


Fig. 5. Discrimination of high-frequency electrical stimuli of varying amplitudes against a mechanical comparison indent of $200\ \mu\text{m}$.

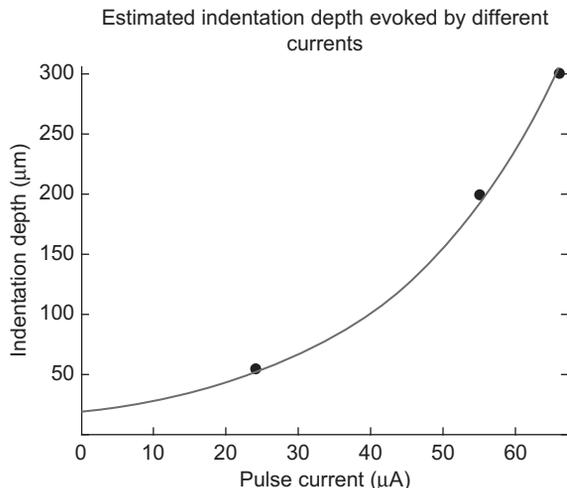


Fig. 6. Estimated relationship between the amplitude of the electrical stimulation and the perceived probe indentation depth.

frequency in the flutter range. More studies are clearly needed to understand how tactile information is coded and represented in somatosensory cortex.

Summary

In this chapter, we summarize what is the current state-of-the-art in using electrical stimuli to provide somatosensory feedback to patients with upper limb prosthesis. Evidence suggests that electrical stimuli can be delivered at several sites along the pathways leading to perception. Each site has its advantages and disadvantages; however, it is clear that what is limiting progress in this field is a fundamental lack of knowledge of how information is encoded in the somatosensory cortex and a need for more precise ways to stimulate multiple neurons in the cortex. It is not until large populations of neurons in cortex can be selectively activated using specified patterns of activity that the dream of an ideal prosthetic hand will be achieved.

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