Enabling Closed-Loop Control of the Modular Prosthetic Limb Through Haptic Feedback

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This article presents an overview of the sensory feedback systems integrated with the Modular Prosthetic Limb that enable closed-loop control. Sensors within each fingertip detect force applied to the fingertip along three axes, heat flux, contact at four locations, and vibration in three axes at a maximum rate of 400 Hz. The system processes data from the sensors in the prosthetic hand and effectuates the feedback either via haptic tactors, which convey force, vibration, or temperature, or alternatively through electrical stimulation via brain implants. Tactor systems are physically mounted at the interface between the user and the prosthetic device, within the socket. Research into direct cortical control and feedback is ongoing, and the system is designed with algorithms that transform the sensor data into a series of electrical stimulation pulses that can be perceived naturally by the brain. Enabling haptic feedback for closed-loop control has the potential to enable dexterous control with a prosthetic device. This article describes the need for sensory feedback systems in prosthetic limbs, the system design components (including the native human sensory system, prosthetic sensors, and actuators) for providing feedback, and the software algorithms used to control the system.

INTRODUCTION

The objective of the Revolutionizing Prosthetics (RP) program, sponsored by the Defense Advanced Research Projects Agency, is not only to develop an advanced prosthetic limb and achieve natural and intuitive feed-forward control, but also to provide natural sensory feedback to the user. That is, develop sensor and actuation mechanisms that can allow a user to feel what the prosthetic hand is feeling, be it force, texture, or temperature. Sensory feedback and closed-loop operation are critical to successfully achieving this vision because they can enable dexterous manipulation for both prosthetic and robotic applications.[1] Specifically, sensory afferent feedback allows the user to actively modulate the force of the prosthetic limb, allows operation without direct visual feedback, and allows tactile exploration of textured objects. Other factors such as improving user acceptance of the prosthetic device or simply the psychological benefit of regaining missing tactile sensations all contribute to the need for haptic feedback.

Enabling sensory feedback in a prosthetic limb involves three main areas of research and development that define the basic architecture of the system: (*i*) developing sensors for the physical prosthetic device, (*ii*) developing feedback devices that either physically stimulate the body using tactors (tactile actuators) or electrically stimulate the nervous system, and (*iii*) implementing algorithms that transform the sensed information into an actuation or stimulation command that will be perceived by the user as a feeling like "touch." In the case of conventional feedback, this could be a linear map (e.g., grip force linearly scaled to force applied somewhere on the patient's body), or in the case of electrical stimulation, it could be a more complex and indirect mapping of grip force to a train of stimulation pulses applied to a given peripheral nerve fiber or location in the somatosensory cortex of the brain.

Effective use and control of an upper-extremity prosthetic device not only requires reliable feed-forward control via interface with the efferent pathways, but also requires integration with sensory afferents. Just as with motor control, providing sensory or haptic feedback to the prosthetic end user can be achieved using a variety of modalities and at various levels of invasiveness. Small electromechanical devices called tactors can provide both low- and high-frequency mechanical stimulation to the skin of a prosthetic wearer. Additionally, temperature feedback can be provided to the user via thermal tactor devices developed as part of the Defense Advanced Research Projects Agency program. In the case of patients who have undergone a surgical remapping of the severed nerves into viable muscle tissue (a procedure known as targeted muscle reinnervation[2]), mechanically stimulating the reinnervated tissue gives the amputee the perception of that stimulation coming from the missing limb.[3,4] More invasive technologies that present the opportunity to display haptic feedback directly to the nervous system include stimulating the peripheral nerve directly via a penetrating electrode implant (e.g., Utah Slant Electrode Array[5]) or stimulating the cortex of the brain directly via penetrating electrodes.[6] The type and quality of haptic feedback provided to the end user varies with each stimulation modality, and multiple design approaches were pursued as part of the RP program. The program goal was to not only provide haptic feedback, but also provide feedback in such a way that the location (somatotopy) and the feedback modality (e.g., pressure, vibration, and temperature) corresponded. In other words, an indirect method of conveying sensory feedback, such as vibration provided to the foot to represent grasp pressure, was not a viable option because this type of sensory substitution automatically increases the cognitive burden (i.e., mental load) because the user has to associate a perceived vibration as a pressure occurring in a completely different location. Rather, grasp pressure of the prosthetic hand should be perceived by the user as pressure felt in the missing (phantom) hand.

With the objective of providing somatotopically matched and modality-matched haptic feedback that will be readily and naturally perceived by the prosthesis user, we and our collaborators pursued enabling technologies for each of the three approaches (tactor design, peripheral nerve stimulation, and cortical stimulation) in parallel.

Presenting haptic information to the end user requires research and development from an actuator perspective, but also from a sensor perspective. Although sensors relating the positions of electromechanical components of the arm as well as joint torques are ubiquitous in robotics, sensing high-quality tactile information at the fingertips is challenging and requires multifunction sensors that are based on an understanding of the sensory feedback process within a native human hand.

SYSTEM DESIGN

Natural Sensory Afferents

Discriminative touch in human skin consists of sensations related to pressure, vibration, shape, texture, etc., which are called epicritic sensations. These sensations are mediated by four main biological mechanoreceptors or afferents: Meissner's corpuscles, Merkel's discs, Pacinian corpuscles, and Ruffini endings. There are approximately 17,000 of these mechanoreceptors in the human hand.[7]

Sensory afferents can also be distinguished by their location and receptive field. Meissner's corpuscles and Merkel's discs are located near the surface of the skin and have small receptive fields, thus conveying precise information from small areas on the skin. Pacinian corpuscles and Ruffini endings are located deeper in the dermis and have much larger receptive fields, conveying coarse sensory information from broader areas on the skin.

Meissner's corpuscles detect flutter and motion. They have high resolution (3–5 mm), detect velocity, and move with the ridged skin of the fingers and palm.[8] They are best at detecting movement across the skin and can assist with grip control.[8,9] Meissner's corpuscles can also detect dynamic touch and pressure.[10] They are the second most sensitive receptor.[11] Merkel's discs detect steady skin indentation and pressure from texture.[10] They have the highest spatial resolution at 0.5 mm,[9] provide tactile and vibration information, and can detect intensity.[8] They can also distinguish skin curvature, pressure, form, texture, and edges.[9] Merkel's discs can detect static touch and pressure. They are the third most sensitive receptor.[11]

Pacinian corpuscles detect deep-tissue vibration and have the widest range of sensitivity to vibration. They also have low spatial resolution at 2 cm.[9] Pacinian corpuscles do not detect steady pressure but rather specialize in light touch and acceleration.[8,9] They are the most sensitive afferent with respect to magnitude and receptive field.[11] Ruffini endings detect steady skin indentation and stretch[10] as well as intensity, pressure, and shear.[8] They have low resolution at 1 cm (see Ref. 9) but are capable of distinguishing lateral force, motion direction, and static force.[9] Ruffini endings are the least sensitive mechanoreceptor.[11]

Thermal senses and pain, also called protopathic sensations, require higher-intensity stimuli than epicritic sensations. These two senses are linked in that extreme temperatures stimulate pain. Thermal receptors, or thermoreceptors, are slowly adapting, bare free nerve endings located in both glabrous and hairy skin. They come in two varieties, one to detect warm and one to detect cold, and both are thought to detect thermal change instead of absolute temperature. Thermoreceptors have a small receptive field (~1 mm in glabrous skin), so object temperature is resolved by comparing the relative activity of different bandwidth-sensitive groups of thermoreceptors.[11]

Because there is a rich suite of sensory receptors within the natural limb, a complete sensory feedback solution of a prosthetic limb will involve a variety of artificial sensors of different modalities, sizes, and frequency responses.

The sensor systems in the prosthetic limb, described in the next section, emulate the native sensory systems of the human body to detect force, vibration, contact, and temperature.

Modular Prosthetic Limb Sensor Matrix

The sensor matrix of the Modular Prosthetic Limb (MPL) system refers to the collection of sensors in the hand of the prosthetic limb. The sensor types include force, torque, vibration, contact, position, heat flux, and temperature. Use of the sensor matrix information applies to hand control as well as haptic feedback to the patient. A set of tactile sensors, located within the fingertip of the MPL, are referred to as the fingertip sensor nodes (FSNs) and are shown in Fig. 1.

Strain gages embedded in each of the fingertips measure both static and dynamic forces. Low-frequency force feedback provided by the fingertip sensors can be used for force control of the MPL with human-in-the-loop as well as local hand grasp (i.e., antislip) control. The fingertip senses three axes of force applied anywhere on the fingertip cap that comprises roughly one half of the distal portion of the phalanx. The FSN software samples each channel of the three-axis force sensor at 200 Hz with 24-bit resolution. To minimize power consumption, only one channel is powered at a time, resulting in an average power draw of 20 mA at 5 V per sensor. Software parameters are used to dynamically recalibrate the sensors to adjust the gain and offset for each axis of the torque sensor to convert the raw counts to engineering units. The need to automatically re-zero the sensor in the course of normal use can arise in response to collisions causing saturation or drift in the baseline response of the sensors.

A group of polyvinylidene fluoride elements overlaid on top of the prosthetic fingertip acts as a contact sensor array. The output of the array is conveyed either by the haptic system or by the neural integration system to the MPL's wearer. This array allows closely spaced surface features such as Braille cells to be resolved and is able to localize applied forces with greater resolution. This information is acquired using the microcontroller's internal 10-bit analog-to-digital converter and sampled at 400 Hz.

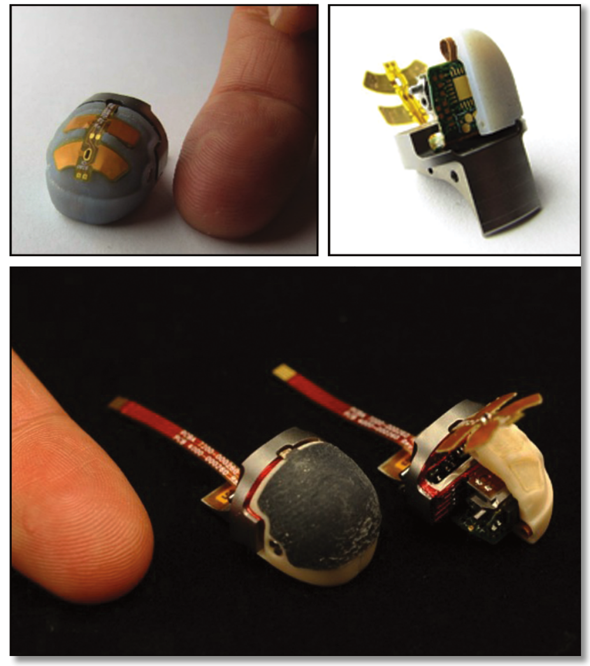

Figure 1. The FSN of the MPL senses force via a three-axis load cell, vibration via a three-axis accelerometer, heat flux, and contact at four locations. (Top left) FSN showing the four contact sensor locations and in comparison to the scale of the human fingertip. (Top right) Partial cross-section of the sensor showing mounting location and back (dorsal) side of the device. (Bottom) Fully assembled FSN with embedded controller and connection leads.

Vibration is sensed by a dedicated three-axis accelerometer. This information is primarily used by the haptic system to enable the prosthesis user to recognize surface textures. The accelerometer is software configurable to ±2 or ±8 G and is sampled at 400 Hz with 8-bit resolution.

Metal is perceived as being colder to the touch than wood when both are at room temperature. This is the result of human skin sensing the rate of heat flow rather than absolute temperature. Thus, it is desirable for the MPL fingertip to sense the heat flux between the MPL and its environment. One challenge involved in meeting the goal of measuring heat flux as opposed to absolute temperature is the need to maintain a temperature close to that of the human hand. The heat flux sensor within the MPL fingertip consists of a self-heating thermistor. A thermistor is a type of resistor of which the resistance varies proportionally to its temperature. The heat flux sensor is only activated within 10 ms after a force threshold has been reached so that sensor activation corresponds to contact with an object. To measure heat flux, the excitation voltage applied to the sensor is regulated using a pulse-width modulation signal and a proportional–integral–derivative controller loop to achieve a constant above-environment temperature. The required voltage needed to maintain this temperature, derived from the 8-bit pulse-width modulation duty cycle, is a measure of the heat loss to the environment. To measure temperature, a thermistor is used. Note that although the thermistor can heat itself and its environment, it cannot actively cool down. Therefore, when the environment temperature exceeds the temperature of the thermistor, it can no longer function as a heat flux sensor. In this situation, the thermistor can only act as a temperature sensor.

In the next section, we describe how the data collected from the sensors of the prosthetic hand are ultimately effectuated by actuators, which provide naturalistic stimulation to the prosthetic wearer.

Tactors

Tactors refer to small electromechanical actuators that physically convey haptic information to an end user. During the first phase of the program, APL and Kinea Design collaboratively developed a multifunction tactor that could deliver significant normal forces (up to 9 N and 10 × 10 mm workspace), shear forces, vibrations (perceptible beyond 200 Hz), and hot/cold sensation to the skin of an amputee. This system provided multimodality and high-quality feedback but to only one or a few sites within a prosthetic user's socket. In the second phase of the program, the tactor device was miniaturized in order to develop a tactor array that would allow salient feedback at numerous locations in the prosthetic socket.

The principal goal of the tactor array is to provide contact (i.e., goal attainment) information corresponding to multiple ventral contact surfaces (as many as the patient can discern and the prosthetic hand can detect). Contact is then displayed by a brief transient force.

The tactor array applies graded pressure but over a much smaller dynamic range than the original multifunction tactor from Phase 1 of the RP program. Instead of a 9-N peak force, a peak force of less than 3 N was the design requirement, which was based on a tradeoff of size versus functionality to the user. This is in keeping with the observation that enclosure, and recognition of grasp stability, is more important than grasp force. Moreover, contact information plus timing provides a good sense of grip force. Just because of the physics of contact, force will ramp up following contact. Because of the compliance of the hand, the rate at which force ramps up is approximately linear. Thus, all that one needs to know is how long after contact to keep squeezing. This is, in some respects, a better way to regulate grip force than by sensing pressure directly and is expected to be a more robust (i.e., stable) strategy and easier for the MPL user to learn.

The tactor is able to produce vibration at 0–200 Hz with a displacement of 0.1 mm at 10 Hz and 0.1 μm at 200 Hz. These design requirements came from the human intact skin vibration threshold in the literature.[12,13] Performing frequency response analysis of tactor data collected in Phase 1 indicated that these magnitudes were feasible to produce. In addition, we noted that although little of the high frequency may be propagated through the tactor transmission, it is perceived via the skin through the vibration of the motor mounting. This is useful because the Pacinian corpuscles, which are responsible for high-frequency vibration response, have a broad receptive field and are not directionally sensitive. It remains to be established that Pacinian corpuscles are responsible for vibration sensing in reinnervated skin, and that reinnervated skin has vibration sensitivity comparable to that of intact finger or forearm.[14]

The threshold of perception of a reinnervated skin subject was 2 g/mm^2, that is 0.1 N when an 8-mm-diameter tactor head is assumed. The minimum perceived amplitude change of the normal force was 0.15–0.2 N.[3] For intact skin, experiments with four subjects using the tactor developed in Phase 1 determined the thresholds were 0.05–0.1 N for chests and less than 0.01 N for fingertips. In addition, it is known that the intact fingertip threshold is lower than 1 mN.[15] Hence the 3-N peak force tactor is able to deliver a wide range of pressure information.

Vibratory feedback can be displayed by the tactor array, but we emphasize that this is much less important than contact. Vibration is needed primarily for sensing textures, but because it is so noticeable, it also provides an opportunity to implement haptic icons. Icons, represented by a stimulation macro, can convey structured messages to communicate non-native information relevant to operation of the prosthetic device, such as "battery low" or "grip force overload." These icons could be used to display quantities other than vibration; for instance, the dynamic range of pressure display could be extended by causing the tactor array to vibrate with increasing amplitude or frequency as the grip force continues to rise.

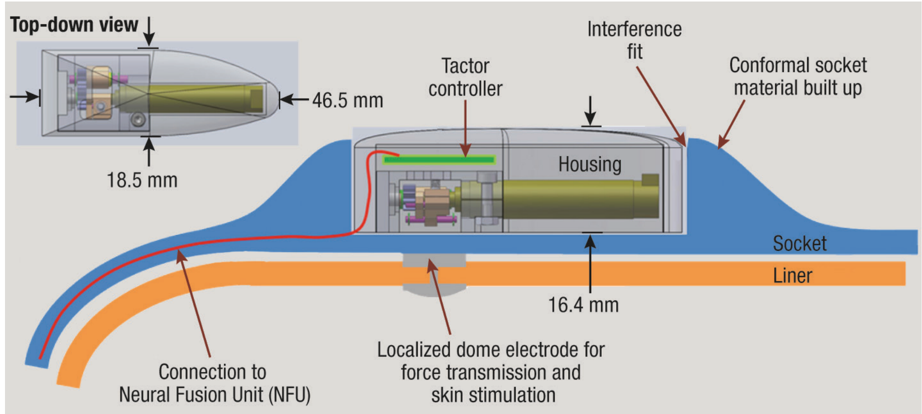

Figure 2. Schematic of the mechanical tactor within the socket system. The actuating element couples to a local electrode to provide vibrotactile stimulation to the user's skin.

Shear force production, although present in the original tactor prototype, has been omitted from the tactor array. To date, during preliminary studies, amputees cannot reliably distinguish shear forces from normal forces. Moreover, the benefit of providing a shear force display is not entirely evident.

The tactor array also has one design variation that allows thermal display. In most cases, we do not expect the added benefit of thermal display to compensate for the added cost, complexity, and power consumption; rather, this type of feedback is more dependent on the user's preference for such feedback.

The actuator elements of the tactor array integrate with the socket and electrode scheme. At present, this involves a gel liner and pass-through electrodes that serve as tactor heads, which thus apply forces directly to the electrodes. There are several reasons for this: real estate on the skin is limited in the case of an amputee since the same locations used for motor control are also used for feedback, and the electrodes are already sized and shaped for comfort within the prosthetic socket.

Components of the tactor array actuation subsystem are protected from sweat via the socket liner. Additionally, the skin, including hair, is protected against being caught in the moving parts of the tactor. If a tactor is needed where an electrode is not, the head of an electrode can still be used as the tactor head.

The tactor array system consists of an actuator, a transmission, a patient interface, and a socket interface. Additionally, the tactor array system houses the tactor controller hardware. The patient interface provides an interface to the MPL user's skin as a noninvasive neural afferent pathway for feedback. The socket interface allows physical attachment and removal of the tactor to the socket for ease of donning and doffing the prosthesis. The phrase "tactor array" refers to simultaneous actuation of several instances of the tactor array at different locations within the socket; as such, the devices are designed to be small and work within close proximity of each other.

The integrated tactor system can be mounted to or removed from the socket as a single unit. Integration of

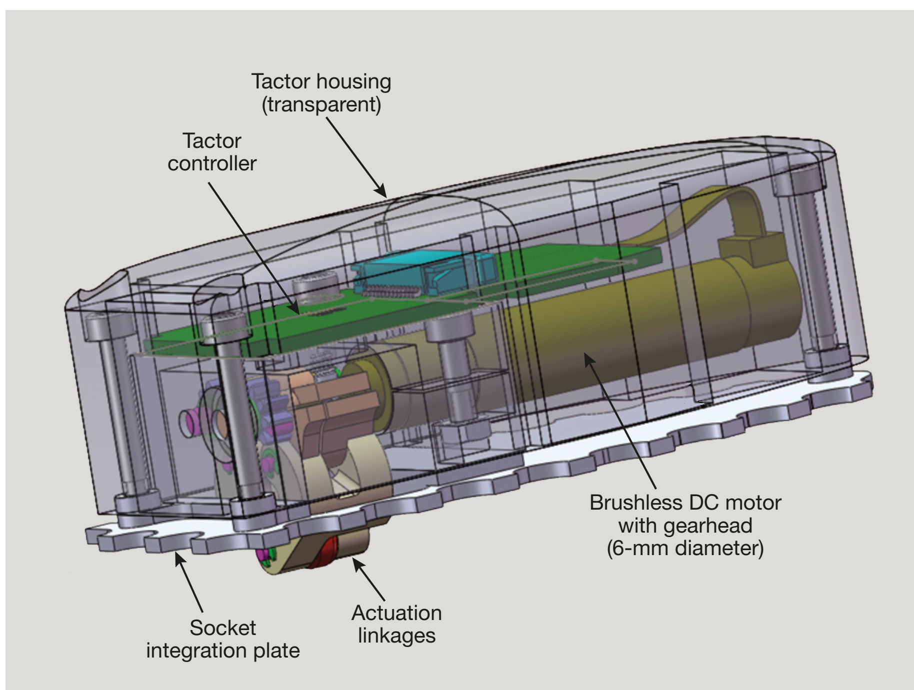

Figure 3. Close-up view of the mechanical tactor and key components.

multiple tactors within the socket for all levels of amputation levels is crucial to the success of the tactor array. Figure 2 depicts the interface design of the mechanical tactor element within the socket system.

The actuator subsystem converts commands received from the main signal-processing controller within the MPL, called the Neural Fusion Unit (NFU), into thermal or mechanical stimuli to the MPL user. The actuator is a crucial component to the tactor and determines the overall performance, weight, and dimension of the tactor array. A COTS brushless DC motor for the tactor array meets the torque, speed, and acceleration requirements. The motor is a 6-mm-diameter and 40-mm-long cylindrical-shape brushless DC motor with 15:1 gear reduction. This actuator includes encoders and hall sensors for angle detection. Figure 3 shows a detailed model of the mechanical tactor.

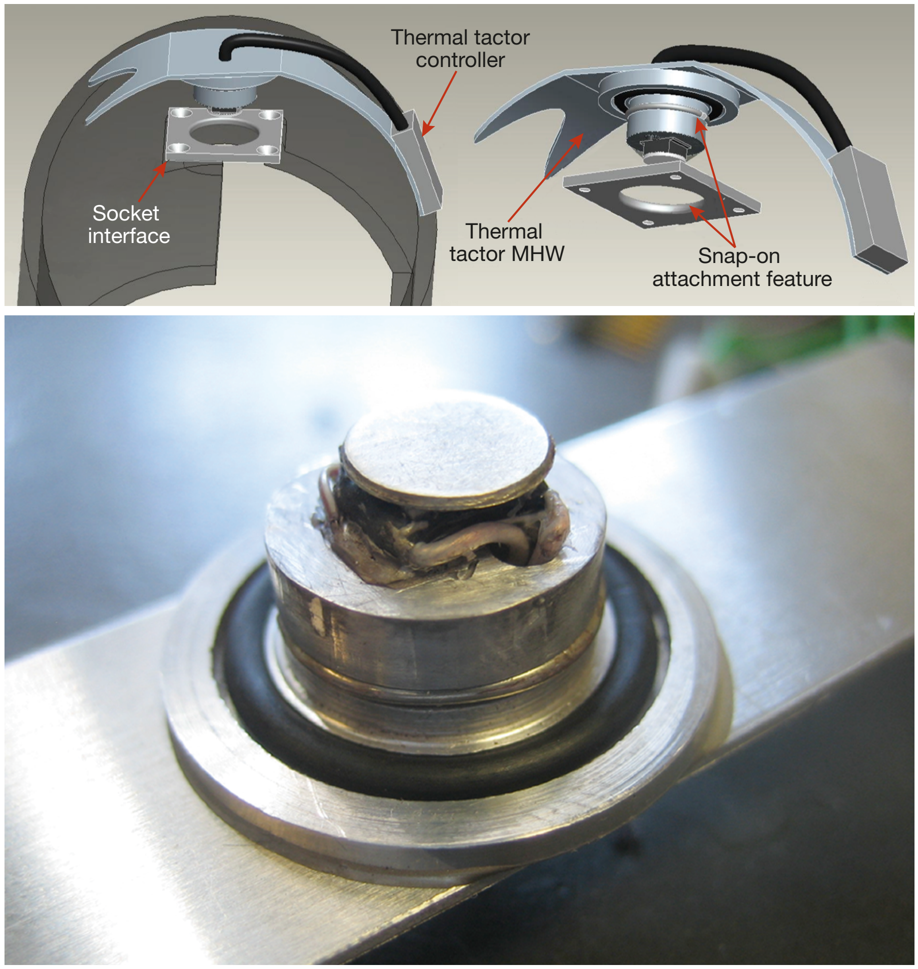

Figure 4. (Top) Diagram of the thermal tactor integration with the socket system. (Bottom) The thermal tactor prototype. MHW, mechanical hardware.

Peltier devices provide thermal feedback using a thermistor as a temperature sensor located within the fingertip sensor. Similar to the mechanical tactor elements, the thermal tactor elements are placed in close proximity to the user's skin through integration within the socket subsystem. Thermal transfer to the users' skin is accomplished through the use of a thermal window, a localized patch of material with a high thermal conductivity. Figure 4 shows a conceptual thermal tactor element integrated with the socket as well as a picture of the designed thermal tactor element.

SENSORY FEEDBACK ALGORITHMS

Sensor Fission

Taken collectively, the sensory encoding algorithms perform the task of aggregating information from all or some of the sensors of the prosthetic limb and convey that information to the user in an intuitive and natural way via different afferent pathways. This sensor-to-afferent mapping process is coordinated by an algorithm called Contextual Sensory Fission (CSF). The central CSF algorithm runs on the NFU and develops a set of sensory "states" that characterize the MPL's current function at a high level (e.g., object has been grasped, object is slipping, hand is exploring environment, etc.). The CSF algorithm then assigns the generation of individual sensory "percepts" to the available feedback channels (noninvasive, moderately invasive, or highly invasive), which are responsible for encoding them in the language of specific stimulators, either mechanical (tactors) or electrical (stimulating electrodes).

The sensors-to-afferents mapping algorithm contrasts the one-to-one haptic feedback paradigm pursued in the Phase 1 effort for targeted nerve reinnervation patients. Previously, a single sensor was used on the Prototype 1 limb that measured grip force (0–100 N) via a strain gauge at the thumb. The sensor readings were processed using a low-pass filter, and the tactor output was controlled using a piecewise linear function. The uniaxial tactor was placed at a location on the patient's chest corresponding to the base of the patient's phantom thumb. The "mapping" was fixed because there was only one sensor in the system and it controlled the one and

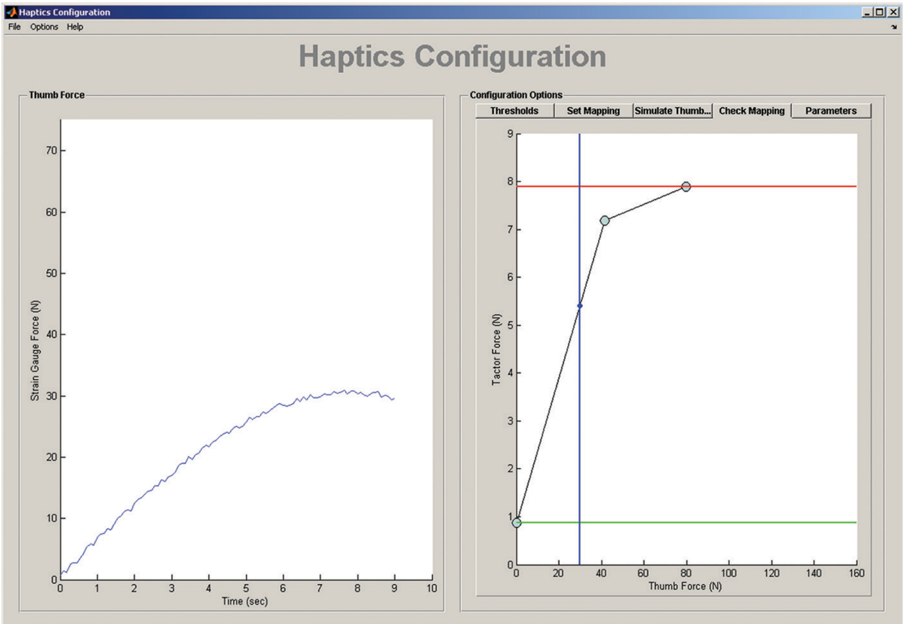

Figure 5. Piecewise linear mapping of MPL grip force input to tactor force output.

only tactor. Sensitivity was controlled by adjusting the control points of the piecewise linear mapping between sensor input and tactor output (Fig. 5).

As opposed to the direct sensor-to-tactor mapping of Phase 1, the Phase 2 effort involved more sensors and a suite of haptic devices ranging from an array of noninvasive tactors to arrays of stimulating electrodes. Stimulation devices may be dynamically actuated in addition to being mapped directly to individual limb sensors. In this context, dynamic actuation means that a device may be actuated on the basis of discrete haptic events: for example, a single-degree-of-freedom tactor might produce a transient "tap" when the hand contacts an object, a high-frequency vibration if slip occurs, and another transient tap when the object is released.

The computational complexity of the sensory encoding algorithms is orders of magnitude greater than that of direct mapping of sensor to tactor. These algorithms can be divided into two parts, one related to the implementation of CSF (the synthesis technique for deriving the context of the prosthetic limb from available sensor information) and one related to the control of the afferent stimulation devices (also known as local sensory encoding algorithms). The CSF algorithm is designed at a level of complexity similar to that of a linear pattern recognition classifier and runs on the NFU. The local sensory encoding algorithms translate a desired percept into a specific pattern of stimulation for either the tactor or the implanted electrodes. The tactor encoding algorithms are designed to run on the NFU and to be relatively simple, whereas the electrode encoding algorithms will run on a separate dedicated microprocessor due to their complexity.

Contextual Sensory Fission

The information from one or more sensors on the MPL can be used synergistically by the NFU to develop an internal model of the state of the limb, which is translated into a variety of percepts to be delivered to the user. These percepts are computed by the CSF algorithm on the basis of the spatiotemporal history of MPL sensor inputs. Information "fission" occurs in the NFU as the percepts are routed to different haptic display devices depending on the sensory feed-

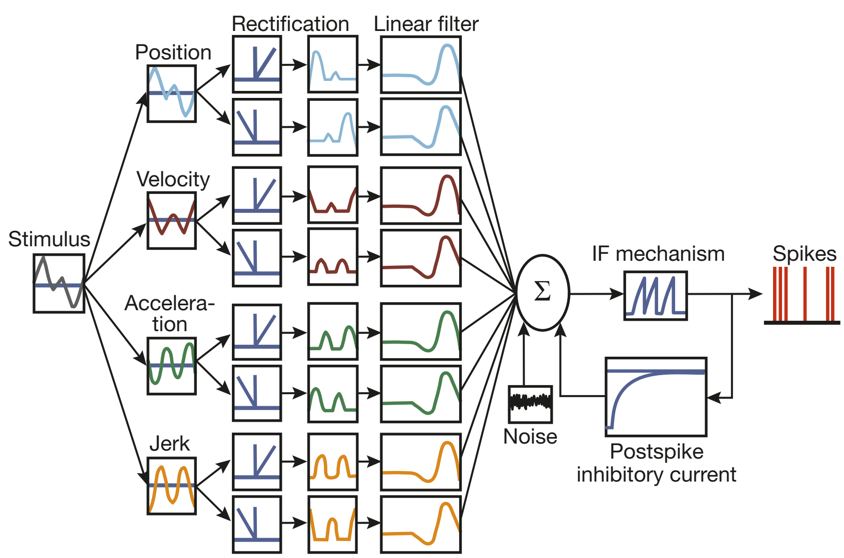

Figure 6. Block diagram of a biofidelic model of a mechanoreceptive peripheral nerve afferent. The model takes a dynamic mechanical stimulus as an input and outputs the expected spike train. In the first stage of the model, components of the input stimulus (time derivatives of position) are extracted. In the next stage, a linear filter is applied to each component. In the final phase, the filtered components are summed along with noise and postinhibitory currents, and the summand is used as the input to an integrate-and-fire (IF) neuron model that generates spikes.

back channels available to the user. Using all available afferent pathways provides a means to deliver not only low-level direct mapping from sensor to stimulation, but also high-level information (e.g., achievement of grasp) based on the current context of limb use (e.g., manipulation). For example, if the user has both noninvasive tactors and multiple peripheral interface devices, the tactors may convey grasp stability information while direct one-to-one sensory mapping is used to control a stimulating electrode array.

The CSF model provides a means to synergistically derive high-level percepts and context from all sensor systems of the MPL. These percepts undergo fission and are split among the available sensory feedback channels to stimulate the user's native sensory system in an intuitive way.

Biofidelic Sensory Stimulation Model

To convey a percept via an afferent stimulation device that interfaces directly with the nervous system, the percept must first be translated into appropriate patterns of electrical stimuli (pulse trains), which in turn induce trains of action potentials in nerve fibers or neurons surrounding the stimulating electrode(s). The intent is to develop models appropriate for brain and spinal cord of the underlying mechanisms such that the sensory transduction can occur in a natural way using a biofidelic sensory stimulation algorithm. In other words, if it is possible to predict the expected neural output to a given mechanical stimulus, then it may be possible to recreate that output as closely as possible via artificial electrical stimulation.

This biofidelic algorithm[16] uses an integrate-and-fire neuron model to simulate the expected output from mechanoreceptive neurons in response to mechanical stimuli. In the example shown in Fig. 6, the stimulus is divided into several components, rectified, filtered, and summed to resolve an action potential firing pattern. This output is then converted into a pattern of electrical stimuli to be delivered to the target neurons, such that their actual output matches the simulated output of the model. This, in turn, should evoke sensory percepts that are perceived intuitively by the user.

SUMMARY

Sensory feedback is a crucial component to the challenge of providing a prosthetic limb system that is both dexterous and naturally controlled by a user. The prosthetic limb must be modular to fit a population of individuals with various types of upper-extremity deficiency (i.e., losing one's arm below the elbow, above the elbow, or at the shoulder, or being paralyzed). However, the feedback systems must also be modular in order to convey haptic force feedback information to a user with the same varying levels of disability. This may involve mechanical stimulation of reinnervated skin where the stimulation is perceived in the mind of the user as originating from the missing limb, or may involve either electrical stimulation of the intact peripheral nerve of the individual or electrical stimulation delivered directly to the somatosensory region of the brain. The dense sensor matrix within the fingertips and hand of the MPL, which detects force, vibration, temperature, and contact, is a key enabler for further research in this area in order to produce salient feedback to a prosthetic user. Linking these sensor and actuator devices are algorithms that provide local feedback loops within the MPL system, simulating reflex-like control as well as mapping and encoding sensor percepts intuitively to the brain of the user.

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