INVITED PAPER

E-Skins: Biomimetic Sensing and Encoding for Upper Limb Prostheses

This article focuses on prosthetic application of e-skin, discussing the physiology of the receptors that encode tactile, thermal, nociceptive, and proprioceptive information and the sensors designed to mimic them.

By Mark M. Iskarous, *Member IEEE*, and Nitish V. Thakor, *Life Fellow IEEE*

ABSTRACT | Prosthetic hands, today, have anthropomorphic, multifinger design. A common control method uses pattern recognition of electromyogram signals. However, these prostheses do not capture the human hand's sensory perception, which is critical for prosthesis embodiment and dexterous object manipulation. This problem can be solved by sensorized electronic skin (e-skin) composed of various sensors that transduce sensory percepts such as touch, pressure, temperature, and pain, just as human skin does. This review will present the physiology of the receptors that encode tactile, thermal, nociceptive, and proprioceptive information. The e-skin is designed to mimic these receptors and their responses. We review each sensor subtype, and its design and performance when embedded in the e-skin. Next, we review the spiking response of the receptors, which are then relayed to sensory nerves and encoded by the brain as sensory percepts. The e-skin system is designed to produce neuromorphic or receptorlike spiking activity. Computational models to mimic these sensory nerve signals are presented and then various methods to interface with the nervous system are explored and compared. We conclude the review with the state of the art in e-skin design and deployment in closed-loop applications that demonstrate the benefits of sensory feedback for amputees.

KEYWORDS | Closed-loop control; e-skin; neural prostheses; neuromorphic encoding; peripheral nerve stimulation; sensory feedback

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(Corresponding author: Mark M. Iskarous.)

M. M. Iskarous is with the Department of Biomedical Engineering, The Johns Hopkins School of Medicine, Baltimore, MD 21205 USA (e-mail: iskarous@jhu.edu).

N. V. Thakor is with the Department of Biomedical Engineering, The Johns Hopkins School of Medicine, Baltimore, MD 21205 USA, and also with the SINAPSE Institute for Neurotechnology, Department of Biomedical Engineering, National University of Singapore, Singapore 117456.

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I. INTRODUCTION

The field of neural engineering has emerged in the last 50 years due to tremendous advances in the fields of electronics, computing, robotics, materials science, neuroscience, and biology [1]. These advances have led to the creation of the first neuroprosthetic devices for the assistance and rehabilitation of people with disabilities such as limb loss and spinal cord injury [2]. The loss of an upper limb has a particularly significant impact on the quality of life for amputees and, as a result, has been a major focus of neuroprosthetic research [3]–[5]. In the past, attention has been given to building motor controllers for prostheses using a variety of neural signals [6]. Typically, myoelectric prostheses decode user motor intention through pattern recognition of electromyogram (EMG) signals from the residual limb of the amputee. The decoded intention is then used to control the prosthetic hand [7]. Up until now, these prostheses have only implemented feedforward motor control, and without sensory feedback, prostheses are unable to fully restore the lost functionality and dexterity of the original limb.

When surveyed, transradial amputees emphasized the need for sensory feedback in order to facilitate a sense of embodiment (that the prosthesis is a part of their body schema) and to enhance prosthesis functionality [8]. Although embodiment is not yet fully understood [9], it is clear that the human body schema is flexible and can even incorporate assistive devices such as prosthetic limbs, leading to better functional outcomes [10]. In addition to embodiment, sensory feedback can improve user control and manipulation of the prosthesis. In biology, active touch sensing is used to gather information about the environment in order to act more effectively in the world [11]. With this inspiration in mind, first-generation sensory neuroprostheses seek to match the human body's capability to "perceive" touch information [12], [13]. A sensory neuroprosthesis acquires sensory percepts from the environment and then relays those perceptions to the amputee. Electronic skins (e-skins), which mimic the functionality of human skin [14]–[16], are being developed to be integrated with upper limb prostheses as a means for acquiring the sensory percepts.

Unnaturalistic sensory feedback through sensory substitution is not sufficient to fully restore desired functionality [17]. As a result, to complete the sensory feedback loop and convey naturalistic perception, information from e-skins must be communicated to the amputee through the nervous system in a biomimetic manner. One approach is to use cortical neural interfaces that record and stimulate neurons directly in the brain [18]–[20]. Although this approach may be the ultimate solution, it is also the most complex and daunting for various reasons (e.g., brain surgery, cortical implantation, and communication with sensory neurons). Alternatively, the successes of cochlear and retinal implants indicate that the clearest path toward sensory restoration for amputees will come about through interfacing with the peripheral nervous system [21]. Peripheral neural interfaces can be established through the intact skin of the amputee's residual arm or through the sensory nerves with electrical stimulation. New developments such as soft implantable devices to record and stimulate peripheral nerves [22], [23] and targeted reinnervation of motor (efferent) and sensory (afferent) nerves [24] provide a toolbox for sensory feedback through the peripheral nervous system.

In this article, we review the science and technology underlying neural e-skins, which sense and encode environmental stimuli in a biomimetic manner [25]. We progress through the information processing pipeline of sensory transduction and encoding in human biology and their analogs in e-skin technology. Finally, we will present the latest applications of e-skins in upper limb sensory neuroprostheses. Although we focus on e-skins for upper limbs, the concepts presented should similarly apply for full-body e-skin applications.

II. BIOLOGICAL SENSORS

The first step toward a biomimetic sensory neuroprosthesis requires understanding how sensory information is initially acquired from the environment by the body using cutaneous biological sensors. Each sensing modality requires specialized sensors, or receptors, that convert a corresponding stimulus into neuronal communication. Neurons communicate through action potentials (or spikes), which propagate along their respective axon and then excite or inhibit the spiking activity of downstream neurons. A critical property of receptors is their arrangement in receptive fields, which characterize the particular region of sensory space that the receptors respond to. For e-skins, tactile perception (i.e., touch) is the most studied sense and will be the focus of this review. Various modalities including tactile, temperature, pain, and proprioception are reviewed next, followed by the appropriate sensors. For an in-depth review of the anatomy and physiology of the sensory neurons involved in touch, see [26].

A. Tactile

The primary biological sensors for tactile sensory information are cutaneous low-threshold mechanoreceptors (LTMRs), which transform mechanical stimuli (such as force) into neuronal communication. The four primary LTMRs are Merkel cells, Meissner corpuscles, Ruffini endings, and Pacinian corpuscles, which are traditionally thought to encode indentation, skin movement, stretch, and vibration, respectively [Fig. 1(a)]. Merkel cells and Ruffini endings are considered slowly adapting (SA) LTMRs because they primarily respond to the static amplitude of force. On the other hand, Meissner and Pacinian corpuscles are considered rapidly adapting (RA) LTMRs because they primarily respond to the onset and cessation of force [Fig. 1(b)]. LTMRs, which encode information about form and texture [27], edge orientation [28], and fingertip force direction [29], communicate through Aβ fibers (conduction velocity from 20 to 100 m/s) [26], [30]–[32]. There are also unmyelinated LTMRs that encode light or pleasant touch sensations through C fibers (0.2–2 m/s) [26], [33]. The density of afferents is varied across different regions of the skin with areas of highest tactile afferent density located on the hand and face, corresponding to the regions of highest tactile acuity and sensitivity [34].

B. Temperature

Temperature sensation is mediated by various types of temperature-dependent thermoreceptors, which modulate neuronal spiking activity. There are two types of cold-sensitive fibers that conduct through Aδ ($<$30 m/s) and unmyelinated C fibers ($<$2 m/s). In addition, there are also warm-sensitive unmyelinated C fibers (0.5–2 m/s) [35], [36]. The information from these thermoreceptors are then used for thermoregulation. The distribution of thermoreceptors is irregular, varies between people, and is asymmetric [37]. Furthermore, hairy skin is more sensitive to temperature than glabrous (smooth) skin. Finally, the sensitivity of thermal sensation increases toward the torso which is opposite to touch and pain that reside more sensitively at the periphery [38].

C. Pain

Nociceptors detect the presence of noxious or harmful stimuli. There are Aδ fibers (5–30 m/s) that respond

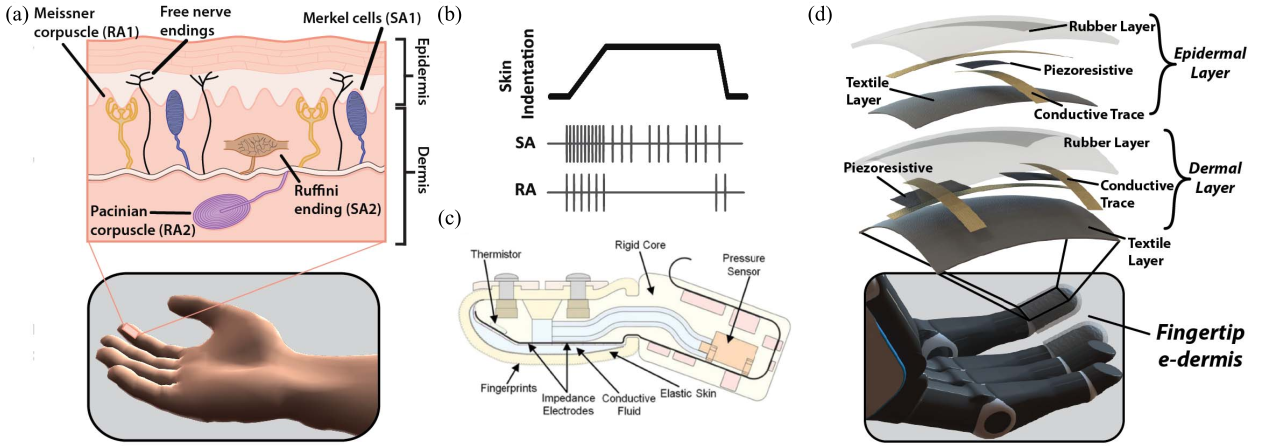

Fig. 1. *(a) Glabrous human skin is composed of two layers that contain different mechanoreceptors for the encoding of tactile sensation. From [50]. Reprinted with permission from AAAS. (b) SA and RA receptors respond to different features of tactile stimuli. 2018 IEEE. Reprinted, with permission, from [51]. (c) The BioTAC sensor uses the pressure and impedance of a conductive fluid to measure external forces, and a thermistor to measure temperature. Reprinted from [52] under the CC-BY license. (d) Bioinspired piezoresistive tactile sensor that is also composed of two layers. From [50]. Reprinted with permission from AAAS.*

to noxious mechanical stimuli and multimodal C fibers (0.4–1.4 m/s) which respond to noxious mechanical, thermal, and chemical stimuli [39]–[41]. Recently discovered "nociceptive Schwann cells" form a mesh network at the subepidermal border in skin and have been shown to transmit nociceptive thermal and mechanical information to unmyelinated nerve fibers [42]. After injury, a decrease in firing threshold for local nociceptive fibers leads to enhanced pain perception, and the surrounding region produces pain to normally innocuous stimuli [41]. These two mechanisms help to avoid further damage. Moreover, experiments with low-frequency electrical stimulation of nociceptors demonstrate that nociceptors exhibit activity-dependent higher order modulation of synaptic plasticity (metaplasticity) [43]. In terms of general nociceptive acuity, glabrous skin follows the pattern of touch in that acuity increases away from the torso, whereas for hairy skin, nociceptive acuity increases toward the torso [44]. The fingertips have high spatial acuity for pain, a "pain fovea," even though there is no corresponding increase in nociceptive fiber density at that location. This observation suggests that pain acuity depends on multimodal neural populations in the spinal cord or cortex that integrate multiple inputs such as tactile and nociceptive information [45].

D. Proprioception

Proprioception refers to the sensation of the position of one part of the body relative to another [46]. This sense is mediated primarily by proprioceptors and supported by cutaneous LTMRs. The two main proprioceptors are muscle spindles, which measure muscle stretch, and golgi tendons, which measure muscle tension through Aα fibers (60–120 m/s) [47], [48]. Cutaneous LTMRs measure skin stretch around joints to convey information about joint angles [46]. The information from these various sources is used to determine limb position, limb movement, load compensation, and motor effort [49].

III. PROSTHESIS SENSORS

Sensors for prosthetic hands seek to transduce various modalities of environmental stimuli with the intention to recreate for an amputee the dexterity and naturalistic sensation of a biological hand. In most cases, standard commercial sensors are used to characterize environmental stimuli. This information can then be encoded biomimetically to be used for sensory feedback. We briefly review some of the most common technological principles underlying these sensors. For more in-depth discussion about tactile sensor technology, materials, and systems, see [53], [54], and [55], respectively. For discussion specifically about e-skins, see [56]. A summary of existing prosthesis sensors is shown in Table 1.

A. Tactile

Tactile sensors are used to measure local force, pressure, and vibration. Different transduction methods can be used to quantify this tactile information. A common solution is to use a piezoresistor, which converts mechanical strain into changes in resistance. Piezoresistive tactile sensors can be constructed using textiles, thick-film resistors, carbon nanotubes, nanocomposite materials, or microelectromechanical systems [57]–[61] and are good for measuring low-frequency (static) forces. Other tactile sensors use piezoelectricity to translate mechanical strain into electrical charge. Piezoelectric materials are effective at measuring high-frequency (dynamic) forces and can be made from lead-zirconate-titanate (PZT) pastes or polyvinylidene fluoride (PVDF) [58], [59], [62], [63]. Piezoelectric and piezoresistive materials have been utilized in

Table 1 Survey of Prosthesis Sensors

Sensor Type	Transduction Methods	Materials	Reference
Tactile	Piezoresistance	Piezoresitive textile	[57]
		Thick film resistor	[58]
		Multiwalled carbon nanotube	[59]
		Carbon nanotube composite dispersed in polyurethane elastomer molded into pyramidal microstructures	[60]
		NiCr microelectromechanical systems embedded in polyimide	[61]
	Piezoelectricity	Lead-zirconate-titanate (PZT) paste	[58]
		Polyvinylidene fluoride (PVDF) thin film	[59]
		PVDF film	[62]
		PVDF film	[63]
	Capacitive	Flexible elastomer	[64]
		Nanocomposites	[65]
		Truncated polydimethylsiloxane (PDMS) pyramid array	[66]
	Electrical Impedance	Conductive fluid	[67]
	Pressure and Electrical Impedance	Conductive fluid	[68]
	Magnetic	Magnetic nanocomposite cilia made of iron nanowires in PDMS	[69]
	Optical	Optical fibers and a flexible beam	[70]
Temperature	Temperature sensitive resistance	Discrete thermistor	[68]
		Thermistor paste	[58]
		Polyamine doped with silver nanoparticles	[65]
Pain	Piezoresistance	Piezoresitive textile	[50]
	Temperature sensitive resistance	Discrete thermistor	[71]
Proprioception	Inertial	6-axis inertial measurement unit (IMU)	[72]
		9-axis IMU	[73]
	Inertial and piezoresistance	IMU and ethylene propylene rubber bending sensor	[74]
	Capacitive	Dielectric elastomer sensor	[75]
	Magnetic	Mylar foil on PDMS glass with ferromagnetic stripes	[76]
	Piezoresistance and optical	Load cell and optical encoder	[77]
	Piezoresistance	6 degrees of freedom load cell	[78]

tactile sensors to reap the advantage of simultaneous measurement of both dynamic and static forces [58], [59]. For applications requiring high sensitivity and resolution, capacitive tactile sensors, which measure changes in capacitance due to tactile forces that affect capacitor geometry, are used. The capacitors can be made from flexible elastomers, nanocomposite materials, or a truncated polydimethylsiloxane (PDMS) pyramid array [64]–[66]. An innovative commercial tactile sensor, the BioTAC, measures changes in electrical impedance of a conductive fluid to characterize forces and changes in fluid pressure to detect microvibrations [67], [68] [Fig. 1(c)]. Finally, novel solutions that use optical beam bending [69] and magnetic field changes [70] have been developed to measure tactile stimuli.

B. Temperature

Temperature sensing usually relies upon thermistors, or temperature-sensitive resistors. Thermistors can be included as discrete components [68], pastes [58], or nanocomposite materials in an e-skin [65].

C. Pain

Typically, a separate sensing device is not specifically incorporated into a prosthetic hand for the purpose of replicating nociceptor transduction of a painful stimulus. For example, extreme measurement patterns from a tactile sensor array can be used to indicate interaction with a sharp object [50] [Fig. 1(d)]. In addition, by using thermistors incorporated into a tactile sensing finger, different object temperatures can be discriminated [71]. This can be extended to detect extremely hot or cold stimuli as a proxy for a painful or dangerous environment. In order to recover from the damage that noxious mechanical or thermal stimuli can cause, rehealable e-skins have been designed to restore their functionality [65].

D. Proprioception

Proprioceptive sensors give information about the position, movement, and loading of the body. For the characterization of position and movement, an inertial measurement unit (IMU) is often used. An IMU contains accelerometers, gyroscopes, and magnetometers to quantify linear acceleration, angular velocity, and orientation, respectively. IMUs can potentially be embedded into e-skins, and the measurements can be combined to get a measure of both position and movement. For instance, in [72], a six-axis IMU measured upper arm abduction/adduction to control the wrist rotation of a prosthetic hand, and in [73], a nine-axis IMU was incorporated with each EMG electrode as a way to improve prosthesis grip classification. Finally, in [74], an IMU on the back of the hand and bending sensors on each finger were used to detect hand and finger-joint motion. Other approaches include wearable stretch sensors that give information about wrist joint movement [75] and an e-skin that incorporates magnetoreception to determine orientation [76]. To measure loading within neuroprosthetic systems, load cells have been integrated to characterize grasp force, internal finger forces, and wrist torques [77], [78].

IV. BIOLOGICAL ENCODING

Cutaneous sensors in skin transform tactile, thermal, nociceptive, and proprioceptive information into spiking activity that propagates to the central nervous system. The pattern of spike trains encodes information about these stimuli and is processed in the spinal cord and brain for local reflex arcs and higher order cortical functions, respectively. For a review of the pathways of cutaneous sensory signals, see [79].

A. Spiking Activity

The principal goal of neural population activity, or "neural codes," is to efficiently encode sensory information to be used for behavioral decisions. Statistical tools have been developed to analyze neural codes and determine how sensory features are encoded and perceived [80]. When decoding spike trains from tactile afferents, both spike rate (frequency information) and spike timing (temporal information) are critical features that encode information about vibration frequency, object shape, and curvature [81], [82]. For example, these statistical tools have revealed that when scanning a texture, mechanoreceptor spiking patterns contract and dilate in response to palpation speed even though the perception is independent of speed [83]. In contrast, the spiking patterns are largely independent of applied palpation force [84].

B. Reflex Pathway

Reflexes are automatic reactions to stimuli that do not require conscious thought. To achieve a quick response time, a typical reflex pathway (or arc) does not need neural communication with the brain and is connected in a closed loop through the spinal cord. The most basic reflex is the muscle stretch reflex that regulates muscle length in response to sudden changes (common contraction in response to muscle stretch). This reflex has been measured to take less than 1 ms and is monosynaptic, meaning that the arc only contains one synapse between one sensory and one motor neuron [85]. A more complex reflex is the nociceptive withdrawal (or flexion) reflex (NWR/NFR), which causes a withdrawal response due to painful stimuli. The magnitude of the withdrawal can be used as a metric for a person's pain experience [86]. The NWR incorporates complex spinal cord processing as it adapts the reflex based on contextual information such as arm position and movement [87]. In addition, purposeful concentration on pain increases the NWR [88], indicating that cortical processes can regulate the behavior of reflexes. The example of the NWR illustrates that reflex pathways are critical for proper motor function, incorporate meaningful processing of sensory information, and express complex behaviors that can be modulated by cortical pathways.

C. Cortical Pathway

As sensory information travels from the spinal cord to the brain, neurons start to respond to higher order, multimodal, integrated features of stimuli. Contrary to traditional thought, different populations of mechanoreceptors (such as Merkel cells and Meissner corpuscles) do not correspond to specific features (such as texture, shape, and vibration). Rather, different afferent population classes are integrated to encode these features as early in the neural pathway as the subcortical regions of the brain [89], [90]. In the primary somatosensory cortex (S1), vector averaging of individual stimulus features computes tactile motion direction [91]. In addition, tactile and proprioceptive information is also integrated to capture object properties [92]. In other cortical regions, tactile and visual information are integrated to encode information about texture and space around the body [93], [94]. A different modality, thermal sensation, is mediated by the insular cortex, which inhibits nociceptive perception at colder temperatures [95]. A study by Ruscheweyh *et al.* [88] showed that distraction strategies reduced pain perception and tactile stimulation reduced the NWR, while focusing on the pain increased the pain perception and the NWR. This study demonstrates that the cortex not only integrates sensory information but also actively modulates sensory perception.

A critical factor for neuroprosthesis design is the reorganization of the brain after amputation and how the neuroprosthesis interacts with and affects neuroplasticity. A clue toward cortical plasticity and organization comes from congenital one-handers whose representation of the missing hand in the cortex is taken over by the body parts that compensate for the missing hand's function [96], indicating that the cortex is organized by functionality and not location. The effect of amputation on cortical structure and connectivity is still debated, but it is evident that there is a significant reorganization. In the primary motor cortex (M1), there seems to be greater connectivity between the hand and neighboring foot regions [97]. For motor planning, there is evidence that visuospatial

Table 2 Survey of Neuromorphic Encoding Models

Model	Biophysically Meaningful	Model Definition	Applications
Hodgkin-Huxley	Yes	[103]	N/A
Leaky Integrate and Fire	No	[104]	Braille stimulation into SA mechanoreceptor response [105]
			Vibratory tactile stimuli into RA mechanoreceptor response [106]
			Robotic joint position and velocity into population encoding [107]
Izhikevich	No	[108]	Touch and pain mechanoreceptor modeling [50]
			Texture discrimination with SA and RA mechanoreceptor response [51]
			Surface roughness recognition with soft neuromorphic approach [109]
			Naturalistic texture categorization [110]
			Discrimination of textural features [111]
			Texture recognition with an extreme learning machine [112]
			Digital hardware realization of cutaneous mechanoreceptors [113]
Mihalas-Niebur	Yes	[114]	Model of mechanotransduction in primate glabrous skin [115]

pathways play a larger role for the residual limb [98]. Growing evidence disputes the notion that, after amputation, the lack of sensory input leads to reorganization of sensory cortical representations. Kikkert *et al.* [99] showed that the topography of the hand and fingers stably lasts decades after amputation. Makin *et al.* [100] argue that the sensory representation remains intact but the network-level connectivity changes are responsible for perceptual differences in amputees. In particular, the sensorimotor cortex weakens its connection to other sensorimotor regions and becomes more strongly connected to the default mode network from which it is normally dissociated [100]. In a later opinion article, they argue that cortical structures are maintained and that the reorganization is mostly in subcortical pathways. The potential stability of cortical structure presents an opportunity to restore sensory perception through cortical interfaces, especially those for whom peripheral nerve interfaces are not an option [101]. In fact, long-term studies with neuroprostheses show that they function as neurorehabilitative devices that help to restore the original cortical structure of the residual limb. Furthermore, cortical reorganization can be used as a qualitative metric to evaluate the effectiveness of prostheses in restoring limb functionality [102]. Ultimately, a greater understanding of the structure and plasticity of the brain is critical for effectively restoring sensorimotor function for amputees using neuroprostheses.

V. NEUROMORPHIC ENCODING

The transformation of sensory information into electrical signals enables feedback loops to improve prosthesis control and functionality. Taking a cue from biology, oftentimes, these electrical signals get encoded as a series of “neuromorphic” spike trains to mimic the signal processing of the body and potentially improve the computational efficiency. Whether or not that encoding step is taken, the sensory information is used for closed-loop control (akin to unconscious processing) or for naturalistic sensory feedback to the prosthesis user (akin to sensory perception). A summary of neuromorphic encoding models and existing applications are shown in Table 2.

A. Neuromorphic Spiking Activity

The neuromorphic encoding of sensory information requires models that describe the way neuronal input signals are translated into spikes. The Hodgkin–Huxley model accurately captures this translation by modeling ion channel conductances as a function of time, membrane potential, and input current [103]. However, while this model is biophysically meaningful and accurate, it is computationally expensive to perform. As a result, numerous mathematical models have been developed to approximate Hodgkin–Huxley dynamics and neuronal behavior [116]. A basic model is the leaky integrate and fire neuron model which has low computational complexity but is unable to reproduce a wide range of neuronal behaviors [104]. The Izhikevich model slightly increases the computational complexity but enables a wide range of neuron spiking phenomenology [108]. It is often used in neuroprosthesis applications to mimic the spiking patterns' characteristic of mechanoreceptors and has been implemented in digital hardware [50], [51], [109]–[113]. The Mihalas–Niebur model has comparable computational complexity but uses biophysically meaningful parameters which allows for more direct translation between biology and prosthetic systems [114]. The Mihalas–Niebur neuron has been used to model mechanoreceptor afferent patterns of macaque monkeys in response to tactile stimuli [115], and an array of 2040 Mihalas–Niebur neurons have been implemented in a low-power CMOS chip [117]. Other neuron models have been used to translate Braille stimulation into SA mechanoreceptor spike trains [105], vibratory tactile stimuli into RA mechanoreceptor spike trains [106], and robotic joint position and velocity information into population spike encoding [107]. There is also a tactile sensor that directly produces afferentlike spiking activity simplistically modeled as ring oscillators (for the purpose of implementing in organic electronics) [118].

After neuromorphic encoding, the next step in the signal processing chain is to analyze the temporal and frequency characteristics of the spike trains. The field of spike train analysis has identified important spike features such as mean spike rate and interspike interval, among others [119]. Furthermore, spike train similarity can be quantified using edit-length metrics such as Victor–Purpura distance [120] for categorization of stimuli. Finally, data-centric models using supervised or unsupervised learning algorithms have also been utilized for classification of spike trains [121], [122].

B. Closed-Loop Control

In this context, closed-loop control refers to the automatic control of the prosthetic system to achieve a goal without the involvement of the prosthesis user (like a reflex). This control is achieved through a feedback loop based on sensory information. For example, in [125], the stiffness of the grasped object is characterized and used to modulate the parameters of the prosthetic hand controller. Another system uses an array of force-sensitive resistors on the upper limb to classify finger motions to be reproduced on a prosthetic arm [126]. The first example uses sensory information to achieve the current goal, while the second one uses sensory information to give context toward determining the next goal. In particular, for a review of tactile sensing computational techniques such as slip detection and force control, see [127], and for a review of tactile perception such as object shape and pose, see [128].

C. Sensory Feedback

A critical goal for upper limb prostheses is also to give natural sensation back to the user since tactile information is critical for object manipulation [129]. A promising demonstration showed that by using peripheral nerve stimulation, amputees felt near-natural touch sensation which allowed them to distinguish between different levels of grasping force without visual or auditory feedback [130]. In the following sections, we will explore the tools and technologies that underlie that demonstration and hold promise for more sophisticated and functional sensory feedback in the future.

1) Sensory Substitution: One approach for sensory feedback is to provide information using another sensory modality that is intact for the amputee such as vision or hearing. For instance, Borisov *et al.* [131] used vibromotors (tactile feedback), LEDs (visual feedback), and a speaker (auditory feedback) to encode information about the prosthesis grip force and finger positions. Although sensory substitution systems can be effective, they can lead to sensory overload, have a limited communication bandwidth, and require significant user training since they are not natural for the user [17]. Thus, sensory substitution can be useful for task-specific systems but do not have long-term potential for general sensory neuroprostheses.

2) Cortical Feedback: Another target for sensory feedback is the brain. Microneuromodulation technologies using electrical, magnetic, optical, chemical, and thermal stimulation are currently being developed and have found initial success for auditory, visual, motor, somatosensory, and cognitive neuroprostheses [132]. For instance, applying intracortical microstimulation (ICMS) to the area of hand representation in S1 elicits pressure and contact location percepts [133]. While exciting, results like these for touch and proprioception depend on biomimetic stimulation patterns [134]. As a result, our understanding of somatosensory information encoding in the brain is the main bottleneck to progress [135]. Ultimately, cortical feedback has significant potential to restore lost sensation but will require significant technological and neuroscientific advancements in order to be viable.

3) Peripheral Nerve Stimulation: Many interfaces have been pioneered to measure and modulate the activity of peripheral nerves [136], [137] [Fig. 2(a)]. Different implementations of peripheral nerve interfaces balance nerve selectivity, channel count, signal stability, and ease of implantation. The least invasive is surface electrodes that rest on the skin and can be used for transcutaneous electrical nerve stimulation (TENS) [138]. Next are extraneural electrodes such as cuff electrodes [139] and flat-interface nerve electrodes (FINE) [140], which surround the nerve fiber to record and stimulate populations of neurons. Intraneural electrodes penetrate nerves in order to get better signal quality and nerve selectivity. This category includes longitudinal intrafascicular electrodes (LIFE) [141], the distributed intrafascicular multielectrode (DIME) [142], the transverse intrafascicular multichannel electrode (TIME) [143], and the Utah slanted electrode array (USEA) [144]. Finally, there are regenerative electrodes that cut the nerve bundles and use chemical induction or electrical stimulation to regenerate nerves through the neural interface [145] such as sieve electrodes [146] or microchannel interfaces [147]. Recent innovations in peripheral nerve interfaces include flexible split ring electrodes [148], a cuff electrode with wireless communication [149], and a battery-free neuromodulator based on triboelectric nanogeneration [150].

An important tool to make peripheral nerve stimulation simpler and more effective is targeted reinnervation. In targeted reinnervation, a peripheral nerve is attached to a nonfunctional muscle (such as the pectoralis major muscle for a shoulder disarticulation amputee), which then acts as a biological signal amplifier. When a motor (efferent) nerve is used, this is called targeted muscle reinnervation (TMR). TMR allows for easier access to nerves and less noisy EMG signals for motor decoding and control. When a sensory

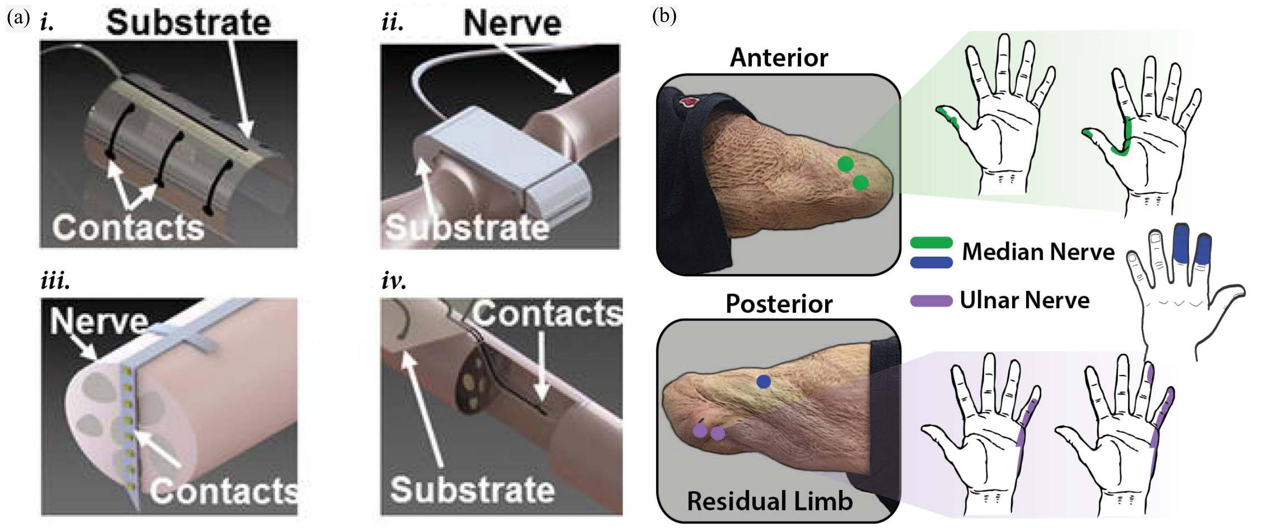

Fig. 2. *(a) Various peripheral nerve interfaces are diagramed. Extraneural interfaces such as (i) cuff electrodes and (ii) FINE surround the nerve. Intraneural interfaces such as (iii) TIME and (iv) LIFE penetrate the nerve. Reprinted by permission from Springer Nature: Springer Medical & Biological Engineering & Computing [123], 2016. (b) Phantom hand activation mapping of the median and ulnar nerves of an amputee subject. TENS was used to elicit a naturalistic sense of touch. 2018 IEEE. Reprinted, with permission, from [124].*

(afferent) nerve is used, this is called targeted sensory reinnervation (TSR). TSR allows for easier and more stable access to record and stimulate peripheral nerves in sensory feedback systems [24]. Over a long period of time, the use of TMR and TSR has been shown to restore the motor and sensory mappings of the residual limb of an amputee in the M1 and S1 cortices, respectively [151], [152].

Over the last few years, these peripheral nerve interfaces have been utilized to elicit naturalistic sensory perceptions in amputees. For instance, using LIFEs, Rossini *et al.* [153] were able to reliably reproduce touch and tingling sensations in different regions of the amputee's phantom hand. Similar results have also been demonstrated using noninvasive TENS for amputees with and without TSR [124]. Both of these results rely upon the sensory mapping of the residual limb to identify the unique peripheral nerve reorganization caused by the amputation [Fig. 2(B)]. In addition, the success of peripheral nerve stimulation for naturalistic sensory feedback depends on the use of biomimetic stimulation patterns to encode sensory information [154]. As a result, several studies have investigated how stimulation pattern parameters such as waveform shape, pulse frequency, pulse amplitude, and pulsewidth affect user perception [155]–[159]. Collectively, these studies reveal that stimulation patterns affect the naturalness, intensity, and specificity of the percept. A recent experiment used various sensory feedback stimulation models for object discrimination tasks and found that more biomimetic stimulation patterns improve task completion time [160]. On the other hand, another study reported that an unnatural tingling sensation triggered by TENS quickly became integrated and interpreted as a touchlike perception [161]. Critically, these results validate the utility of neuromorphic stimulation patterns for functional tasks while also showing that sensory feedback that is not fully biofidelic can be interpreted to improve the task performance.

4) Embodiment and Training: For neuroprosthetic systems with sensory feedback, it is important to consider how successfully the amputee is able to incorporate the prosthesis into their body schema, as well as the training process needed to achieve intuitive sensing and control. A range of studies have reported improvements in embodiment using both noninvasive [25], [50], [161], [162] and invasive nerve interfaces [160], [163], [164], with the invasive interfaces showing greater improvement in embodiment [164]. Although these improvements can be measured using quantitative metrics such as a shift in phantom hand position [163], most of the time, they are characterized through subjective reporting from amputees. For instance, amputees report higher agency over their prosthesis movements [162], that the objects they interact with are directly causing their sensations in their phantom hand [50], and that their phantom hand exhibits a greater range of motion [163]. These subjective experiences help the amputee to quickly incorporate and rely on the sensory feedback [161], even referring to the prosthetic limb as their "hand" [163]. In addition, the feedback provides emotional benefits such as increased enjoyment and intimacy in social interactions [160]. Importantly, the benefits of naturalistic sensory feedback do not require high cognitive attention from the amputees as the task performance improvements persist when simultaneously performing a cognitively demanding task [160], [164].

Achieving intuitive sensing and control of these closed-loop systems requires training to get the amputee accustomed with sensory feedback. Training sessions can last from a few minutes to a few hours [160], [161], with performance gains manifesting within the first

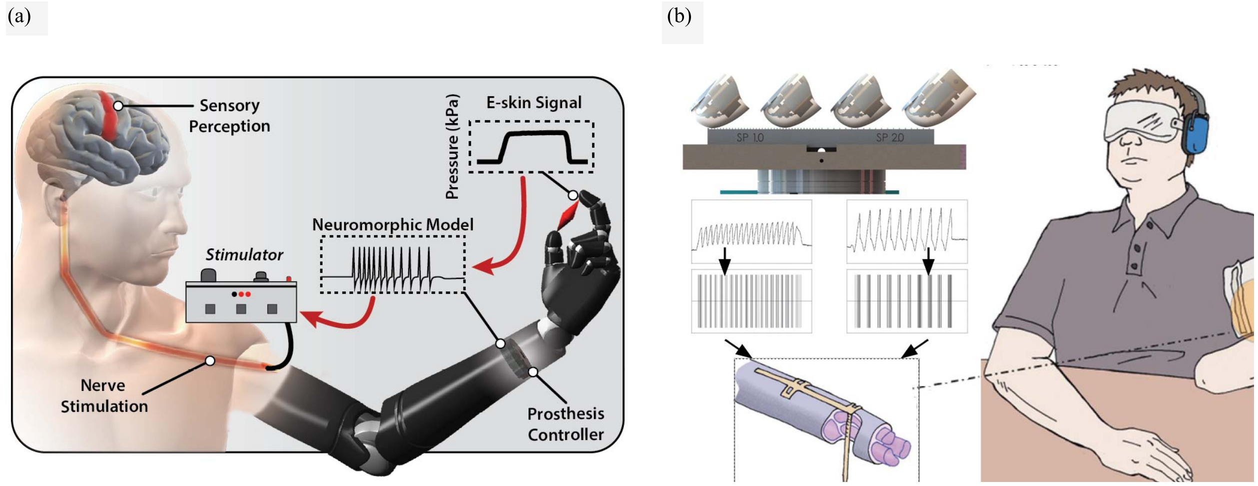

Fig. 3. *(a) System diagram for a sensory neuroprosthesis that transforms tactile sensor readings from an e-skin into neuromorphic spikes, which are then used to elicit naturalistic tactile perception using peripheral nerve stimulation. In this scenario, the amputee felt pain when interacting with a sharp object and the object is automatically released. From [50]. Reprinted with permission from AAAS. (b) Artificial fingertip with tactile sensing scans textures with a range of coarseness. The sensor readings are translated into spiking activity using the Izhikevich model. This is used to stimulate the median nerve and enables discrimination of textures. Adapted from [111] under the CC-BY license.*

session [162], [165]. These gains can continue to grow with further training sessions over a period of months [165]. Long-term success of sensory feedback systems relies upon the stability of the elicited sensory percepts and muscle activation patterns over time. Both invasive [160] and noninvasive [50] sensory feedback systems have demonstrated sensory and motor stability over a period of 14 and 11 months, respectively.

VI. E-SKIN SYSTEMS AND APPLICATIONS

Combining biomimetic sensing systems with neuromorphic encoding schemes and novel neural interfaces has enabled the design of sensory neuroprostheses which implement functional improvements that assist the user in daily life and improve the agency and embodiment of the prosthesis [Fig. 3(a)].

A. Grip and Slip

Grip regulation (compliant grasping) and slip prevention are subconscious reflexes in intact upper limbs and can be automatically modulated in prostheses. This is a straightforward control scheme that significantly improves the prosthesis functionality. Using textile-based piezoresistive tactile sensors, Osborn *et al.* [166] developed a closed-loop upper limb prosthetic system that measured contact force to attenuate grip strength and detect slip events, which resulted in fewer broken and fallen objects. After converting the sensor readings to neuromorphic spikes (with the leaky integrate and fire neuron model) and using the spike trains as the input to the control scheme, they found that the spike-based algorithm performed as well as the algorithm that operated directly on the raw sensor readings [167]. Integration of this tactile sensing system with a neuromorphic camera to detect object shape and orientation further improved prosthesis functionality in an object relocation task [168]. Even without automatic grip control, sensory restoration through nerve stimulation can improve the amputee's ability to control their prosthesis. For example, using TENS on the residual median and ulnar nerves of amputees can induce a sensation of paresthesia in the phantom limb that can be used in functional tasks such as applying different levels of grip force [161]. Recently, close-to-natural force and slippage sensations were elicited using cuff and intraneural electrodes, and this enabled the amputee to better control their prosthesis for fine grasp and manipulation tasks [165].

B. Object Recognition and Texture Discrimination

Tactile sensors that could be embedded in e-skins have also been used to implement various applications such as curvature detection [169], object shape and size discrimination [170], roughness classification [109], [171], and object rigidity and deformability characterization [172]. Texture discrimination is another common application of tactile sensors. The BioTAC pressure-based tactile sensor was used with simulated exploratory movements to discriminate between different textures and object compliances [52], [173]. Others have encoded the tactile information as spike trains using the Izhikevich neuron model and then used unsupervised classification based on a Gaussian mixture model, k-nearest neighbors clustering, or an extreme learning machine chip to discriminate between textures [51], [110], [112]. Oddo *et al.* [111] used the Izhikevich model to mimic an SA mechanoreceptor afferent and stimulated the median nerve with the resulting spike train (TIME interface). This elicited a mechanical sensation in the amputee that enabled them to successfully discriminate between textures of various coarseness [111] [Fig. 3(b)].

C. Emerging Applications and Technology

Prostheses with nociceptive sensory feedback are just beginning to be developed. The most prominent example comes from Osborn *et al.* who used a multilayered tactile sensor array to discriminate between objects of different curvatures. The tactile sensor readings from each layer were converted to spike trains using the Izhikevich neuron model. Highly localized activation of a tactile sensor array indicated a sharp object. The activation pattern was identified as a noxious stimulus and resulted in the prosthetic hand releasing the sharp object reflexively, and the simultaneous stimulation of residual nerves through TENS induced a natural pain sensation in the amputee [50] [Fig. 3(a)].

The implementation of proprioceptive feedback in upper limb prostheses is also a newly emerging field. A principal source of difficulty is the impracticality of mimicking the large number of proprioceptors present in the body [47]. Ramakonar *et al.* [174] establish a potential basis for proprioceptive feedback with the observation that amputees experience the rubber hand illusion. The illusion can be exploited to improve perceptual embodiment of the prosthetic limb through the use of TENS or tactile stimulators on the residual limb. The conversion of joint position and velocity of a robotic arm into population spike encoding has been demonstrated [107] and can be used for peripheral nerve stimulation. Recently, TIME implants have been used to stimulate tactile afferents of the lower palm as a form of sensory substitution. In this case, the amputee was able to use different tactile sensations to discriminate between finger joint angle positions, which allowed for object size characterization [164]. In another case, a kinesthetic illusion of complex grip movements was induced using vibratory tactile stimulation of residual muscles. The amputee quickly integrated this information to improve their control of the prosthesis, which instilled a greater sense of agency [162]. In the future, IMUs and stretch sensors can be used to gather information about overall limb position and movement. Overall, the approaches of neuromorphic encoding, sensory substitution, and kinesthetic illusions as a long-term solution for proprioceptive feedback are still being investigated.

To greatly expand the utility of sensory neuroprosthetic systems, e-skins must capture multimodal stimuli at enough scale to cover large surface areas such as an arm. Recently, a rehealable e-skin has been developed that has tactile, temperature, flow, and humidity sensing capabilities. By applying heat, the sensor array can be fixed after damage or can be made malleable in order to form shapes that conform to a desired surface [65]. Another e-skin architecture has been developed that neuromorphically models mechanoreceptors and uses asynchronous coding to enable low-latency transmission of thermotactile information with high temporal precision in large-scale arrays. This e-skin has been used for slip detection, texture classification, and object curvature and hardness perception. It is also flexible and robust to physical damage [175]. These two examples demonstrate the growing effort to develop scalable, robust, and flexible e-skins with innovations in multimodal sensing and information encoding to enable advanced sensory feedback applications.

VII. CONCLUSION

For upper limb amputees, sensory feedback is a pressing need that will enable dexterous manipulation of objects in their environment. By understanding the way that skin transduces sensory information into neural spiking activity and how the information is integrated and encoded in the brain, a pathway is illuminated toward restoring naturalistic perception with neural prostheses using e-skins. With the current state of technology and neuroscientific understanding, peripheral nerve interfaces present the clearest path forward and have demonstrated exciting applications that will significantly improve the lives of amputees. ■

REFERENCES

[1] A. Prochazka, "Neurophysiology and neural engineering: A review," *J. Neurophysiol.*, vol. 118, no. 2, pp. 1292–1309, 2017.

[2] B. C. Eapen, D. P. Murphy, and D. X. Cifu, "Neuroprosthetics in amputee and brain injury rehabilitation," *Exp. Neurol*, vol. 287, pp. 479–485, Jan. 2017.

[3] B. Lee, F. J. Attenello, C. Y. Liu, M. P. McLoughlin, and M. L. J. Apuzzo, "Recapitulating flesh with silicon and steel: Advancements in upper extremity robotic prosthetics," *World Neurosurgery*, vol. 81, nos. 5–6, pp. 730–741, May/Jun. 2014.

[4] A. E. Schultz and T. A. Kuiken, "Neural interfaces for control of upper limb prostheses: The state of the art and future possibilities," *PM&R*, vol. 3, no. 1, pp. 55–67, 2011.

[5] R. G. E. Clement, K. E. Bugler, and C. W. Oliver, "Bionic prosthetic hands: A review of present technology and future aspirations," *Surgeon*, vol. 9, no. 6, pp. 336–340, 2011.

[6] N. V. Thakor, "Translating the brain-machine interface," *Sci. Transl. Med.*, vol. 5, no. 210, p. 210ps17, Nov. 2013.

[7] E. D. Engeberg, "A physiological basis for control of a prosthetic hand," *Biomed. Signal Process. Control*, vol. 8, no. 1, pp. 6–15, Jan. 2013.

[8] U. Wijk and I. Carlsson, "Forearm amputees' views of prosthesis use and sensory feedback," *J. Hand Therapy*, vol. 28, no. 3, pp. 269–278, Jul./Sep. 2015.

[9] M. S. Blumberg and J. C. Dooley, "Phantom limbs, neuroprosthetics, and the developmental origins of embodiment," *Trends Neurosci.*, vol. 40, no. 10, pp. 603–612, Oct. 2017.

[10] M. Pazzaglia and M. Molinari, "The embodiment of assistive devices—From wheelchair to exoskeleton," *Phys. Life Rev.*, vol. 16, pp. 163–175, Mar. 2016.

[11] T. J. Prescott, M. E. Diamond, and A. M. Wing, "Active touch sensing," *Philos. Trans. Roy. Soc. London B, Biol. Sci.*, vol. 366, no. 1581, pp. 2989–2995, 2011.

[12] W. M. B. Tiest, "Tactual perception of material properties," *Vis. Res.*, vol. 50, no. 24, pp. 2775–2782, Dec. 2010.

[13] J. Dargahi and S. Najarian, "Human tactile perception as a standard for artificial tactile sensing—A review," *Int. J. Med. Robot. Comput. Assist. Surgery*, vol. 1, no. 1, pp. 23–35, Jun. 2004.

[14] R. S. Dahiya, G. Metta, M. Valle, and G. Sandini, "Tactile sensing—From humans to humanoids," *IEEE Trans. Robot.*, vol. 26, no. 1, pp. 1–20, Feb. 2010.

[15] M. L. Hammock, A. Chortos, B. C.-K. Tee, J. B.-H. Tok, and Z. Bao, "25th anniversary article: The evolution of electronic skin (E-Skin): A brief history, design considerations, and recent progress," *Adv. Mater.*, vol. 25, no. 42, pp. 5997–6038, Nov. 2013,

[16] A. Chortos, J. Liu, and Z. Bao, "Pursuing prosthetic electronic skin," *Nature Mater.*, vol. 15, p. 937, Jul. 2016.

[17] Á. Kristjánsson *et al.*, "Designing sensory-substitution devices: Principles, pitfalls and potential," *Restorative Neurol. Neurosci.*, vol. 34, no. 5, pp. 769–787, 2016.

[18] K. Woeppel, Q. Yang, and X. T. Cui, "Recent advances in neural electrode–tissue interfaces,"

Current Opinion Biomed. Eng., vol. 4, pp. 21–31, Dec. 2017.

[19] A. P. Tsu, M. J. Burish, J. GodLove, and K. Ganguly, "Cortical neuroprosthetics from a clinical perspective," *Neurobiol. Disease*, vol. 83, pp. 154–160, Nov. 2015.

[20] M. A. Lebedev and M. A. Nicolelis, "Chapter 3—Toward a whole-body neuroprosthetic," in *Brain Machine Interfaces: Implications for Science, Clinical Practice and Society* (Progress in Brain Research), vol. 194, J. Schouenborg, M. Garwicz, and N. Danielsen, Eds. Amsterdam, The Netherlands: Elsevier, 2011, pp. 47–60.

[21] D. J. Weber, R. Friesen, and L. E. Miller, "Interfacing the somatosensory system to restore touch and proprioception: Essential considerations," *J. Motor Behav.*, vol. 44, no. 6, pp. 403–418, 2012.

[22] Z. Fekete and A. Pongrácz, "Multifunctional soft implants to monitor and control neural activity in the central and peripheral nervous system: A review," *Sens. Actuators B, Chem.*, vol. 243, pp. 1214–1223, May 2017.

[23] S. Micera and X. Navarro, "Chapter 2 bidirectional interfaces with the peripheral nervous system," *Int. Rev. Neurobiol.*, vol. 86, pp. 23–38, Feb. 2009.

[24] B. T. Carlsen, P. Prigge, and J. Peterson, "Upper extremity limb loss: Functional restoration from prosthesis and targeted reinnervation to transplantation," *J. Hand Therapy*, vol. 27, no. 2, pp. 106–114, Apr./Jun. 2014.

[25] R. Dahiya, "E-Skin: From humanoids to humans," *Proc. IEEE*, vol. 107, no. 2, pp. 247–252, Feb. 2019.

[26] V. E. Abraira and D. D. Ginty, "The sensory neurons of touch," *Neuron*, vol. 79, no. 4, pp. 618–639, Aug. 2013.

[27] K. O. Johnson and S. S. Hsiao, "Neural mechanisms of tactual form and texture perception," *Annu. Rev. Neurosci.*, vol. 15, no. 1, pp. 227–250, 1992.

[28] J. A. Pruszynski and R. S. Johansson, "Edge-orientation processing in first-order tactile neurons," *Nature Neurosci.*, vol. 17, no. 10, pp. 1404–1409, 2014.

[29] I. Birznieks, P. Jenmalm, A. W. Goodwin, and R. S. Johansson, "Encoding of direction of fingertip forces by human tactile afferents," *J. Neurosci.*, vol. 21, no. 20, pp. 8222–8237, 2001.

[30] Å. B. Vallbo and R. S. Johansson, "Properties of cutaneous mechanoreceptors in the human hand related to touch sensation," *Human Neurobiol.*, vol. 3, no. 1, pp. 3–14, 1984.

[31] K. O. Johnson, "The roles and functions of cutaneous mechanoreceptors," *Current Opin. Neurobiol.*, vol. 11, no. 4, pp. 455–461, Aug. 2001.

[32] H. Haeberle and E. A. Lumpkin, "Merkel cells in somatosensation," *Chemosensory Perception*, vol. 1, no. 2, pp. 110–118, 2008.

[33] J. Wessberg, H. Olausson, K. W. Fernström, and K. B. Vallbo, "Receptive field properties of unmyelinated tactile afferents in the human skin," *J. Neurophysiol.*, vol. 89, no. 3, pp. 1567–1575, 2003.

[34] R. Ackerley, I. Carlsson, H. Wester, H. Olausson, and H. B. Wasling, "Touch perceptions across skin sites: Differences between sensitivity, direction discrimination and pleasantness," *Frontiers Behav. Neurosci.*, vol. 8, p. 54, Feb. 2014.

[35] W. Jänig, "Chapter 2—Peripheral thermoreceptors in innocuous temperature detection," in *Thermoregulation: From Basic Neuroscience to Clinical Neurology Part I* (Handbook of Clinical Neurology), vol. 156, A. A. Romanovsky, Ed. Amsterdam, The Netherlands: Elsevier, 2018, pp. 47–56.

[36] M. Campero, T. K. Baumann, H. Bostock, and J. L. Ochoa, "Human cutaneous C fibres activated by cooling, heating and menthol," *J. Physiol.*, vol. 587, no. 23, pp. 5633–5652, Dec. 2009.

[37] F. Yang, G. Chen, S. Zhou, D. Han, J. Xu, and S. Xu, "Mapping sensory spots for moderate temperatures on the back of hand," *Sensors*, vol. 17, no. 12, p. 2802, 2017.

[38] D. Filingeri, H. Zhang, and E. A. Arens, "Thermosensory micromapping of warm and cold sensitivity across glabrous and hairy skin of male and female hands and feet," *J. Appl. Physiol.*, vol. 125, no. 3, pp. 723–736, 2018.

[39] E. R. Perl, "Myelinated afferent fibres innervating the primate skin and their response to noxious stimuli," *J. Physiol.*, vol. 197, no. 3, pp. 593–615, Aug. 1968.

[40] E. S. J. Smith and G. R. Lewin, "Nociceptors: A phylogenetic view," *J. Comparative Physiol. A*, vol. 195, no. 12, pp. 1089–1106, 2009.

[41] A. E. Dubin and A. Patapoutian, "Nociceptors: The sensors of the pain pathway," *J. Clin. Invest.*, vol. 120, no. 11, pp. 3760–3772, 2010.

[42] H. Abdo *et al.*, "Specialized cutaneous Schwann cells initiate pain sensation," *Science*, vol. 365, no. 6454, pp. 695–699, 2019.

[43] W. Magerl, N. Hansen, R.-D. Treede, and T. Klein, "The human pain system exhibits higher-order plasticity (metaplasticity)," *Neurobiol. Learn. Memory*, vol. 154, pp. 112–120, Oct. 2018.

[44] F. Mancini *et al.*, "Whole-body mapping of spatial acuity for pain and touch," *Ann. Neurol.*, vol. 75, no. 6, pp. 917–924, 2014.

[45] F. Mancini, C. F. Sambo, J. D. Ramirez, D. L. H. Bennett, P. Haggard, and G. D. Iannetti, "A fovea for pain at the fingertips," *Current Biol.*, vol. 23, no. 6, pp. 496–500, Mar. 2013.

[46] U. Proske, "The role of muscle proprioceptors in human limb position sense: A hypothesis," *J. Anatomy*, vol. 227, no. 2, pp. 178–183, Aug. 2015.

[47] A. Prochazka, "Sensory control of normal movement and of movement aided by neural prostheses," *J. Anatomy*, vol. 227, no. 2, pp. 167–177, Aug. 2015.

[48] A. C. Guyton and J. E. Hall, *Textbook of Medical Physiology*, 11th ed. Amsterdam, The Netherlands: Elsevier, 2006.

[49] U. Proske and S. C. Gandevia, "The proprioceptive senses: Their roles in signaling body shape, body position and movement, and muscle force," *Physiolog. Rev.*, vol. 92, no. 4, pp. 1651–1697, 2012.

[50] L. E. Osborn *et al.*, "Prosthesis with neuromorphic multilayered e-dermis perceives touch and pain," *Sci. Robot.*, vol. 3, no. 19, 2018, Art. no. eaat3818.

[51] M. M. Iskarous, H. H. Nguyen, L. E. Osborn, J. L. Betthauser, and N. V. Thakor, "Unsupervised learning and adaptive classification of neuromorphic tactile encoding of textures," in *Proc. IEEE Biomed. Circuits Syst. Conf. (BioCAS)*, Oct. 2018, pp. 1–4.

[52] Z. Su, J. A. Fishel, T. Yamamoto, and G. E. Loeb, "Use of tactile feedback to control exploratory movements to characterize object compliance," *Frontiers Neurorobotics*, vol. 6, p. 7, Jul. 2012.

[53] C. Chi, X. Sun, N. Xue, T. Li, and C. Liu, "Recent progress in technologies for tactile sensors," *Sensors*, vol. 18, no. 4, p. 948, 2018.

[54] T. Yang, D. Xie, Z. Li, and H. Zhu, "Recent advances in wearable tactile sensors: Materials, sensing mechanisms, and device performance," *Mater. Sci. Eng. R, Rep.*, vol. 115, pp. 1–37, May 2017.

[55] L. Zou, C. Ge, Z. J. Wang, E. Cretu, and X. Li, "Novel tactile sensor technology and smart tactile sensing systems: A review," *Sensors*, vol. 17, no. 11, p. 2653, 2017.

[56] A. Chortos and Z. Bao, "Skin-inspired electronic devices," *Mater. Today*, vol. 17, no. 7, pp. 321–331, Sep. 2014.

[57] L. Osborn, H. Nguyen, J. Betthauser, R. Kaliki, and N. Thakor, "Biologically inspired multi-layered synthetic skin for tactile feedback in prosthetic limbs," in *Proc. IEEE Eng. Med. Biol. Soc. (EMBC)*, Aug. 2016, pp. 4622–4625.

[58] A. Cranny, D. P. J. Cotton, P. H. Chappell, S. P. Beeby, and N. M. White, "Thick-film force and slip sensors for a prosthetic hand," *Sens. Actuators A, Phys.*, vols. 123–124, pp. 162–171, Sep. 2005.

[59] W. Liu *et al.*, "Preliminary study on piezoresistive and piezoelectric properties of a double-layer soft material for tactile sensing," *Mater. Sci.*, vol. 21, no. 2, pp. 238–243, 2015.

[60] B. C.-K. Tee *et al.*, "A skin-inspired organic digital mechanoreceptor," *Science*, vol. 350, no. 6258, pp. 313–316, Oct. 2015.

[61] R. Kilaru, Z. Çelik-Butler, D. P. Butler, and I. E. Gönenli, "NiCr MEMS tactile sensors embedded in polyimide toward smart skin," *J. Microelectromech. Syst.*, vol. 22, no. 2, pp. 349–355, 2013.

[62] P. Yu, W. Liu, C. Gu, X. Cheng, and X. Fu, "Flexible piezoelectric tactile sensor array for dynamic three-axis force measurement," *Sensors*, vol. 16, no. 6, p. 819, 2016.

[63] A. Song, Y. Han, H. Hu, and J. Li, "A novel texture sensor for fabric texture measurement and classification," *IEEE Trans. Instrum. Meas.*, vol. 63, no. 7, pp. 1739–1747, Jul. 2014.

[64] P. Laszczak, L. Jiang, D. L. Bader, D. Moser, and S. Zahedi, "Development and validation of a 3D-printed interfacial stress sensor for prosthetic applications," *Med. Eng. Phys.*, vol. 37, no. 1, pp. 132–137, 2015.

[65] Z. Zou, C. Zhu, Y. Li, X. Lei, W. Zhang, and J. Xiao, "Rehealable, fully recyclable, and malleable electronic skin enabled by dynamic covalent thermoset nanocomposite," *Sci. Adv.*, vol. 4, no. 2, 2018, Art. no. eaaq0508.

[66] G. Liang, Y. Wang, D. Mei, K. Xi, and Z. Chen, "Flexible capacitive tactile sensor array with truncated pyramids as dielectric layer for three-axis force measurement," *J. Microelectromech. Syst.*, vol. 24, no. 5, pp. 1510–1519, 2015.

[67] N. Wettels, V. J. Santos, R. S. Johansson, and G. E. Loeb, "Biomimetic tactile sensor array," *Adv. Robot.*, vol. 22, no. 8, pp. 829–849, 2008.

[68] C. H. Lin, T. W. Erickson, J. A. Fishel, N. Wettels, and G. E. Loeb, "Signal processing and fabrication of a biomimetic tactile sensor array with thermal, force and microvibration modalities," in *Proc. IEEE Int. Conf. Robot. Biomimetics (ROBIO)*, Dec. 2009, pp. 129–134.

[69] R. Ahmadi, M. Packirisamy, J. Dargahi, and R. Cecere, "Discretely loaded beam-type optical fiber tactile sensor for tissue manipulation and palpation in minimally invasive robotic surgery," *IEEE Sensors J.*, vol. 12, no. 1, pp. 22–32, Jan. 2012.

[70] A. Alfadhel and J. Kosel, "Magnetic nanocomposite cilia tactile sensor," *Adv. Mater.*, vol. 27, no. 47, pp. 7888–7892, 2015.

[71] M. C. Jimenez and J. A. Fishel, "Evaluation of force, vibration and thermal tactile feedback in prosthetic limbs," in *Proc. IEEE Haptics Symp. (HAPTICS)*, Feb. 2014, pp. 437–441.

[72] D. A. Bennett and M. Goldfarb, "IMU-based wrist rotation control of a transradial myoelectric prosthesis," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 26, no. 2, pp. 419–427, Feb. 2018.

[73] A. Krasoulis, I. Kyranou, M. S. Erden, K. Nazarpour, and S. Vijayakumar, "Improved prosthetic hand control with concurrent use of myoelectric and inertial measurements," *J. Neuroeng. Rehabil.*, vol. 14, pp. 1–14, Jul. 2017.

[74] X. Li, R. Wen, Z. Shen, Z. Wang, K. D. K. Luk, and Y. Hu, "A wearable detector for simultaneous finger joint motion measurement," *IEEE Trans. Biomed. Circuits Syst.*, vol. 12, no. 3, pp. 644–654, Jun. 2018.

[75] B. Huang *et al.*, "Wearable stretch sensors for motion measurement of the wrist joint based on dielectric elastomers," *Sensors*, vol. 17, no. 12, p. 2708, 2017.

[76] G. S. C. Bermúdez, H. Fuchs, L. Bischoff, J. Fassbender, and D. Makarov, "Electronic-skin compasses for geomagnetic field-driven artificial magnetoreception and interactive electronics," *Nature Electron.*, vol. 1, no. 11, pp. 589–595, 2018.

[77] W. D. Memberg and P. E. Crago, "A grasp force and position sensor for the quantitative evaluation of neuroprosthetic hand grasp systems," *IEEE Trans. Rehabil. Eng.*, vol. 3, no. 2, pp. 175–181, Jun. 1995.

[78] M. Lawrence, G.-P. Gross, M. Lang, A. Kuhn, T. Keller, and M. Morari, "Assessment of finger forces and wrist torques for functional grasp using new multichannel textile neuroprostheses," *Artif. Organs*, vol. 32, no. 8, pp. 634–638, 2008.
[79] F. McGlone and D. Reilly, "The cutaneous sensory system," *Neurosci. Biobehavioral Rev.*, vol. 34, no. 2, pp. 148–159, 2010.
[80] S. Panzeri, C. D. Harvey, E. Piasini, P. E. Latham, and T. Fellin, "Cracking the neural code for sensory perception by combining statistics, intervention, and behavior," *Neuron*, vol. 93, no. 3, pp. 491–507, Feb. 2017.
[81] I. Birznieks and R. M. Vickery, "Spike timing matters in novel neuronal code involved in vibrotactile frequency perception," *Current Biol.*, vol. 27, no. 10, pp. 1485–1490, 2017.
[82] H. P. Saal, X. Wang, and S. J. Bensmaia, "Importance of spike timing in touch: An analogy with hearing?" *Current Opinion Neurobiol.*, vol. 40, pp. 142–149, Oct. 2016.
[83] A. I. Weber *et al.*, "Spatial and temporal codes mediate the tactile perception of natural textures," *Proc. Nat. Acad. Sci. USA*, vol. 110, no. 42, pp. 17107–17112, 2013.
[84] H. P. Saal, A. K. Suresh, L. E. Solorzano, A. I. Weber, and S. J. Bensmaia, "The effect of contact force on the responses of tactile nerve fibers to scanned textures," *Neuroscience*, vol. 389, pp. 99–103, Oct. 2018.
[85] E. Kandel, J. Schwartz, T. Jessell, S. Siegelbaum, and A. J. Hudspeth, *Principles of Neural Science*, 5th ed. New York, NY, USA: McGraw-Hill, 2013.
[86] V. Skljarevski and N. M. Ramadan, "The nociceptive flexion reflex in humans—Review article," *Pain*, vol. 96, no. 1, pp. 3–8, 2002.
[87] M. Serrao *et al.*, "Kinematic and electromyographic study of the nociceptive withdrawal reflex in the upper limbs during rest and movement," *J. Neurosci.*, vol. 26, no. 13, pp. 3505–3513, 2006.
[88] R. Ruscheweyh, A. Kreusch, C. Albers, J. Sommer, and M. Marziniak, "The effect of distraction strategies on pain perception and the nociceptive flexor reflex (RIII reflex)," *Pain*, vol. 152, no. 11, pp. 2662–2671, Nov. 2011.
[89] H. P. Saal and S. J. Bensmaia, "Touch is a team effort: Interplay of submodalities in cutaneous sensibility," *Trends Neurosci.*, vol. 37, no. 12, pp. 689–697, 2014.
[90] H. Jöntell, F. Bengtsson, P. Geborek, A. Spanne, A. V. Terekhov, and V. Hayward, "Segregation of tactile input features in neurons of the cuneate nucleus," *Neuron*, vol. 83, no. 6, pp. 1444–1452, 2014.
[91] Y.-C. Pei, S. S. Hsiao, J. C. Craig, and S. J. Bensmaia, "Neural mechanisms of tactile motion integration in somatosensory cortex," *Neuron*, vol. 69, no. 3, pp. 536–547, Feb. 2011.
[92] S. Kim, M. Gomez-Ramirez, P. H. Thakur, and S. S. Hsiao, "Multimodal interactions between proprioceptive and cutaneous signals in primary somatosensory cortex," *Neuron*, vol. 86, no. 2, pp. 555–566, Apr. 2015.
[93] K. Sathian *et al.*, "Dual pathways for haptic and visual perception of spatial and texture information," *NeuroImage*, vol. 57, no. 2, pp. 462–475, Jul. 2011.
[94] E. Macaluso and A. Maravita, "The representation of space near the body through touch and vision," *Neuropsychologia*, vol. 48, no. 3, pp. 782–795, Feb. 2010.
[95] A. Craig, K. Chen, D. Bandy, and E. M. Reiman, "Thermosensory activation of insular cortex," *Nature Neurosci.*, vol. 3, pp. 184–190, Feb. 2000.
[96] A. Hahamy *et al.*, "Representation of multiple body parts in the missing-hand territory of congenital one-handers," *Current Biol.*, vol. 27, no. 9, pp. 1350–1355, May 2017.
[97] X. J. Yu *et al.*, "Somatotopic reorganization of hand representation in bilateral arm amputees with or without special foot movement skill," *Brain Res.*, vol. 1546, pp. 9–17, Feb. 2014.
[98] L. Williams, N. Pirouz, J. C. Mizelle, W. Cusack, R. Kistenberg, and L. A. Wheaton, "Remodeling of cortical activity for motor control following upper limb loss," *Clin. Neurophysiol.*, vol. 127, no. 9, pp. 3128–3134, Sep. 2016.
[99] S. Kikkert *et al.*, "Revealing the neural fingerprints of a missing hand," *Elife*, vol. 5, Aug. 2016, Art. no. e15292.
[100] T. R. Makin, N. Filippini, E. P. Duff, D. H. Slater, I. Tracey, and H. Johansen-Berg, "Network-level reorganisation of functional connectivity following arm amputation," *NeuroImage*, vol. 114, pp. 217–225, Jul. 2015.
[101] T. R. Makin and S. J. Bensmaia, "Stability of sensory topographies in adult cortex," *Trends Cognit. Sci.*, vol. 21, no. 3, pp. 195–204, 2017.
[102] G. D. Pino, E. Guglielmelli, and P. M. Rossini, "Neuroplasticity in amputees: Main implications on bidirectional interfacing of cybernetic hand prostheses," *Progr. Neurobiol.*, vol. 88, no. 2, pp. 114–126, Jun. 2009.
[103] A. L. Hodgkin and A. F. Huxley, "A quantitative description of membrane current and its application to conduction and excitation in nerve," *J. Physiol.*, vol. 117, no. 4, pp. 500–544, 1952.
[104] R. B. Stein, "A theoretical analysis of neuronal variability," *Biophys. J.*, vol. 5, no. 2, pp. 173–194, 1965.
[105] L. L. Bologna, J. Pinoteau, R. Brasselet, M. Maggiali, and A. Arleo, "Encoding/decoding of first and second order tactile afferents in a neurorobotic application," *J. Physiol.-Paris*, vol. 105, nos. 1–3, pp. 25–35, 2011.
[106] Z. Yi and Y. Zhang, "Bio-inspired tactile FA-I spiking generation under sinusoidal stimuli," *J. Bionic Eng.*, vol. 13, no. 4, pp. 612–621, Oct. 2016.
[107] N. R. Luque, J. A. Garrido, J. Ralli, J. J. Laredo, and E. Ros, "From sensors to spikes: Evolving receptive fields to enhance sensorimotor information in a robot-arm," *Int. J. Neural Syst.*, vol. 22, no. 4, 2012, Art. no. 1250013.
[108] E. M. Izhikevich, "Simple model of spiking neurons," *IEEE Trans. Neural Netw.*, vol. 14, no. 6, pp. 1569–1572, Nov. 2003.
[109] Z. Yi and Y. Zhang, "Recognizing tactile surface roughness with a biomimetic fingertip: A soft neuromorphic approach," *Neurocomputing*, vol. 244, pp. 102–111, Jun. 2017.
[110] U. B. Rongala, A. Mazzoni, and C. M. Oddo, "Neuromorphic artificial touch for categorization of naturalistic textures," *IEEE Trans. Neural Netw. Learn. Syst.*, vol. 28, no. 4, pp. 819–829, Apr. 2015.
[111] C. M. Oddo *et al.*, "Intraneural stimulation elicits discrimination of textural features by artificial fingertip in intact and amputee humans," *Elife*, vol. 5, Mar. 2016, Art. no. e09148.
[112] M. Rasouli, Y. Chen, A. Basu, S. L. Kukreja, and N. V. Thakor, "An extreme learning machine-based neuromorphic tactile sensing system for texture recognition," *IEEE Trans. Biomed. Circuits Syst.*, vol. 12, no. 2, pp. 313–325, Apr. 2018.
[113] N. Salimi-Nezhad, M. Amiri, E. Falotico, and C. Laschi, "A digital hardware realization for spiking model of cutaneous mechanoreceptor," *Frontiers Neurosci.*, vol. 12, p. 322, Jun. 2018.
[114] Ş. Mihalaş and E. Niebur, "A generalized linear integrate-and-fire neural model produces diverse spiking behaviors," *Neural Comput.*, vol. 21, no. 3, pp. 704–718, 2009.
[115] Y. Dong, S. Mihalas, S. S. Kim, T. Yoshioka, S. Bensmaia, and E. Niebur, "A simple model of mechanotransduction in primate glabrous skin," *J. Neurophysiol.*, vol. 109, no. 5, pp. 1350–1359, 2013.
[116] E. M. Izhikevich, "Which model to use for cortical spiking neurons?" *IEEE Trans. Neural Netw.*, vol. 15, no. 5, pp. 1063–1070, Sep. 2004.
[117] J. L. Molin, A. Eisape, C. S. Thakur, V. Varghese, C. Brandli, and R. Etienne-Cummings, "Low-power, low-mismatch, highly-dense array of VLSI Mihalas-Niebur neurons," in *Proc. IEEE Int. Symp. Circuits Syst. (ISCAS)*, May 2017, pp. 1–4.
[118] Y. Kim *et al.*, "A bioinspired flexible organic artificial afferent nerve," *Science*, vol. 360, no. 6392, pp. 998–1003, 2018.
[119] J. Aljadeff, B. J. Lansdell, A. L. Fairhall, and D. Kleinfeld, "Analysis of neuronal spike trains, deconstructed," *Neuron*, vol. 91, no. 2, pp. 221–259, Jul. 2016.
[120] J. D. Victor and K. P. Purpura, "Nature and precision of temporal coding in visual cortex: A metric-space analysis," *J. Neurophysiol.*, vol. 76, no. 2, pp. 1310–1326, 1996.
[121] Z. Yi, Y. Zhang, and J. Peters, "Biomimetic tactile sensors and signal processing with spike trains: A review," *Sens. Actuators A, Phys.*, vol. 269, pp. 41–52, Jan. 2018.
[122] R. Gütig, "To spike, or when to spike?" *Current Opinion Neurobiol.*, vol. 25, pp. 134–139, Apr. 2014.
[123] S. Nag and N. V. Thakor, "Implantable neurotechnologies: Electrical stimulation and applications," *Med. Biol. Eng. Comput.*, vol. 54, no. 1, pp. 63–76, Jan. 2016.
[124] L. Osborn *et al.*, "Targeted transcutaneous electrical nerve stimulation for phantom limb sensory feedback," in *Proc. IEEE Biomed. Circuits Syst. (BioCAS)*, Oct. 2017, pp. 1–4.
[125] R. Andrecioli and E. D. Engeberg, "Adaptive sliding manifold slope via grasped object stiffness detection with a prosthetic hand," *Mechatronics*, vol. 23, no. 8, pp. 1171–1179, Dec. 2013.
[126] N. Li, D. Yang, L. Jiang, H. Liu, and H. Cai, "Combined use of FSR sensor array and SVM classifier for finger motion recognition based on pressure distribution map," *J. Bionic Eng.*, vol. 9, no. 1, pp. 39–47, 2012.
[127] Z. Kappassov, J.-A. Corrales, and V. Perdereau, "Tactile sensing in dexterous robot hands—Review," *Robot. Auto. Syst.*, vol. 74, pp. 195–220, Dec. 2015.
[128] S. Luo, J. Bimbo, R. Dahiya, and H. Liu, "Robotic tactile perception of object properties: A review," *Mechatronics*, vol. 48, pp. 54–67, Dec. 2017.
[129] B. P. Delhaye, H. P. Saal, and S. J. Bensmaia, "Key considerations in designing a somatosensory neuroprosthesis," *J. Physiol.-Paris*, vol. 110, no. 4, pp. 402–408, Nov. 2016.
[130] S. Raspopovic *et al.*, "Restoring natural sensory feedback in real-time bidirectional hand prostheses," *Sci. Transl. Med.*, vol. 6, no. 222, p. 222ra19, 2014.
[131] I. I. Borisov, O. V. Borisova, S. V. Krivosheev, R. V. Oleynik, and S. S. Reznikov, "Prototyping of EMG-controlled prosthetic hand with sensory system," *IFAC-PapersOnLine*, vol. 50, no. 1, pp. 16027–16031, 2017.
[132] M. E. Urdaneta, A. S. Koivuniemi, and K. J. Otto, "Central nervous system microstimulation: Towards selective micro-neuromodulation," *Current Opinion Biomed. Eng.*, vol. 4, pp. 65–77, Dec. 2017.
[133] S. N. Flesher *et al.*, "Intracortical microstimulation of human somatosensory cortex," *Sci. Transl. Med.*, vol. 8, no. 361, p. 361ra141, Oct. 2016.
[134] G. A. Tabot, S. S. Kim, J. E. Winberry, and S. J. Bensmaia, "Restoring tactile and proprioceptive sensation through a brain interface," *Neurobiol. Disease*, vol. 83, pp. 191–198, Nov. 2015.
[135] S. S. Hsiao, M. Fettiplace, and B. Darbandi, "Chapter 5—Sensory feedback for upper limb prostheses," in *Enhancing Performance for Action and Perception* (Progress in Brain Research), vol. 192, A. Green, C. E. Chapman, J. F. Kalaska, and F. Lepore, Eds. Amsterdam, The Netherlands: Elsevier, 2011, pp. 69–81.
[136] A. L. Ciancio *et al.*, "Control of prosthetic hands via the peripheral nervous system," *Frontiers Neurosci.*, vol. 10, p. 116, Apr. 2016.
[137] S. Lee and C. Lee, "Toward advanced neural interfaces for the peripheral nervous system (PNS) and their future applications," *Current Opinion Biomed. Eng.*, vol. 6, pp. 130–137, Jun. 2018.
[138] K. A. Sluka and D. Walsh, "Transcutaneous electrical nerve stimulation: Basic science mechanisms and clinical effectiveness," *J. Pain*, vol. 4, no. 3, pp. 109–121, 2003.
[139] R. B. Stein, D. Charles, T. Gordon, J.-A. Hoffer, and J. Jhamandas, "Impedance properties of

metal electrodes for chronic recording from mammalian nerves," *IEEE Trans. Biomed. Eng.*, vol. BME-25, no. 6, pp. 532–537, Nov. 1978.
[140] D. J. Tyler and D. M. Durand, "Functionally selective peripheral nerve stimulation with a flat interface nerve electrode," *IEEE Trans. Neural Syst. Rehabil. Eng.*, vol. 10, no. 4, pp. 294–303, Dec. 2002.
[141] K. Yoshida and R. B. Stein, "Characterization of signals and noise rejection with bipolar longitudinal intrafascicular electrodes," *IEEE Trans. Biomed. Eng.*, vol. 46, no. 2, pp. 226–234, Feb. 1999.
[142] A. K. Thota *et al.*, "A system and method to interface with multiple groups of axons in several fascicles of peripheral nerves," *J. Neurosci. Methods*, vol. 244, pp. 78–84, 2015.
[143] T. Boretius *et al.*, "A transverse intrafascicular multichannel electrode (TIME) to interface with the peripheral nerve," *Biosensors Bioelectron.*, vol. 26, no. 1, pp. 62–69, 2010.
[144] A. Branner, R. B. Stein, and R. A. Normann, "Selective stimulation of cat sciatic nerve using an array of varying-length microelectrodes," *J. Neurophysiol.*, vol. 85, pp. 1585–1594, Apr. 2001.
[145] K. Haastert-Talini and C. Grothe, "Chapter five—Electrical stimulation for promoting peripheral nerve regeneration," in *Tissue Engineering of the Peripheral Nerve* (International Review of Neurobiology), vol. 109, S. Geuna, I. Perroteau, P. Tos, and B. Battiston, Eds. New York, NY, USA: Academic, 2013, pp. 111–124.
[146] P. M. Klinge *et al.*, "Immunohistochemical characterization of axonal sprouting and reactive tissue changes after long-term implantation of a polyimide sieve electrode to the transected adult rat sciatic nerve," *Biomaterials*, vol. 22, no. 17, pp. 2333–2343, Sep. 2001.
[147] J. J. FitzGerald *et al.*, "A regenerative microchannel neural interface for recording from and stimulating peripheral axons *in vivo*," *J. Neural Eng.*, vol. 9, no. 1, 2012, Art. no. 016010.
[148] S. Lee *et al.*, "Selective stimulation and neural recording on peripheral nerves using flexible split ring electrodes," *Sens. Actuators B, Chem.*, vol. 242, pp. 1165–1170, 2017.
[149] A. Shon, J.-U. Chu, J. Jung, H. Kim, and I. Youn, "An implantable wireless neural interface system for simultaneous recording and stimulation of peripheral nerve with a single cuff electrode," *Sensors*, vol. 18, no. 1, p. 1, 2018.
[150] S. Lee *et al.*, "Battery-free neuromodulator for peripheral nerve direct stimulation," *Nano Energy*, vol. 50, pp. 148–158, Aug. 2018.
[151] A. Chen, J. Yao, T. Kuiken, and J. P. A. Dewald, "Cortical motor activity and reorganization following upper-limb amputation and subsequent targeted reinnervation," *NeuroImage, Clin.*, vol. 3, pp. 498–506, Jan. 2013.
[152] J. Yao, A. Chen, T. Kuiken, C. Carmona, and J. Dewald, "Sensory cortical re-mapping following upper-limb amputation and subsequent targeted reinnervation: A case report," *NeuroImage, Clin.*, vol. 8, pp. 329–336, Jan. 2015.
[153] P. M. Rossini *et al.*, "Double nerve intraneural interface implant on a human amputee for robotic hand control," *Clin. Neurophysiol.*, vol. 121, no. 5, pp. 777–783, 2010.
[154] H. P. Saal and S. J. Bensmaia, "Biomimetic approaches to bionic touch through a peripheral nerve interface," *Neuropsychologia*, vol. 79, pp. 344–353, Dec. 2015.
[155] C. Pasluosta, P. Kiele, and T. Stieglitz, "Paradigms for restoration of somatosensory feedback via stimulation of the peripheral nervous system," *Clin. Neurophysiol.*, vol. 129, no. 4, pp. 851–862, Apr. 2018.
[156] D. W. Tan, M. A. Schiefer, M. W. Keith, J. R. Anderson, J. Tyler, and D. J. Tyler, "A neural interface provides long-term stable natural touch perception," *Sci. Transl. Med.*, vol. 6, no. 257, p. 257ra138, 2014.
[157] E. L. Graczyk, M. A. Schiefer, H. P. Saal, B. P. Delhaye, S. J. Bensmaia, and D. J. Tyler, "The neural basis of perceived intensity in natural and artificial touch," *Sci. Transl. Med.*, vol. 8, p. 362ra142, Oct. 2016.
[158] G. Valle *et al.*, "Biomimetic intraneural sensory feedback enhances sensation naturalness, tactile sensitivity, and manual dexterity in a bidirectional prosthesis," *Neuron*, vol. 100, no. 1, pp. 37–45, Oct. 2018.
[159] G. Valle *et al.*, "Comparison of linear frequency and amplitude modulation for intraneural sensory feedback in bidirectional hand prostheses," *Sci. Rep.*, vol. 8, no. 1, 2018, Art. no. 16666.
[160] J. A. George *et al.*, "Biomimetic sensory feedback through peripheral nerve stimulation improves dexterous use of a bionic hand," *Sci. Robot.*, vol. 4, no. 32, 2019, Art. no. eaax2352.
[161] E. D'Anna *et al.*, "A somatotopic bidirectional hand prosthesis with transcutaneous electrical nerve stimulation based sensory feedback," *Sci. Rep.*, vol. 7, Sep. 2017, Art. no. 10930.
[162] P. D. Marasco *et al.*, "Illusory movement perception improves motor control for prosthetic hands," *Sci. Transl. Med.*, vol. 10, no. 432, 2018, Art. no. eaao6990.
[163] D. M. Page *et al.*, "Motor control and sensory feedback enhance prosthesis embodiment and reduce phantom pain after long-term hand amputation," *Front. Hum. Neurosci.*, vol. 12, p. 352, Jan. 2018.
[164] E. D'Anna *et al.*, "A closed-loop hand prosthesis with simultaneous intraneural tactile and position feedback," *Sci. Robot.*, vol. 4, no. 27, 2019, Art. no. eaau8892.
[165] L. Zollo *et al.*, "Restoring tactile sensations via neural interfaces for real-time force-and-slippage closed-loop control of bionic hands," *Sci. Robot.*, vol. 4, no. 27, 2019, Art. no. eaau9924.
[166] L. Osborn, R. R. Kaliki, A. B. Soares, and N. V. Thakor, "Neuromimetic event-based detection for closed-loop tactile feedback control of upper limb prostheses," *IEEE Trans. Haptics*, vol. 9, no. 2, pp. 196–206, Apr./Jun. 2016.
[167] L. Osborn, H. Nguyen, R. Kaliki, and N. V. Thakor, "Prosthesis grip force modulation using neuromorphic tactile sensing," in *Proc. Myoelectr. Controls Symp. (MEC)*, 2017, pp. 188–191.
[168] M. Hays, L. Osborn, R. Ghosh, M. Iskarous, C. Hunt, and N. V. Thakor, "Neuromorphic vision and tactile fusion for upper limb prosthesis control," in *Proc. 9th Int. IEEE/EMBS Conf. Neural Eng. (NER)*, Mar. 2019, pp. 981–984.
[169] W. Lee, J. Cabibihan, and N. V. Thakor, "Bio-mimetic strategies for tactile sensing," in *Proc. Sensors*, Nov. 2013, pp. 1–4.
[170] S. Datta, A. Khasnobish, A. Konar, D. N. Tibarewala, and R. Janarthanan, "Object shape and size recognition from tactile images," in *Proc. Int. Conf. Control Commun. Comput. (ICCC)*, Dec. 2013, pp. 16–21.
[171] L. Qin, Z. Yi, and Y. Zhang, "Unsupervised surface roughness discrimination based on bio-inspired artificial fingertip," *Sens. Actuators A, Phys.*, vol. 269, pp. 483–490, Jan. 2018.
[172] A. Drimus, G. Kootstra, A. Bilberg, and D. Kragic, "Design of a flexible tactile sensor for classification of rigid and deformable objects," *Robot. Auto. Syst.*, vol. 62, no. 1, pp. 3–15, Jan. 2014.
[173] J. A. Fishel and G. E. Loeb, "Bayesian exploration for intelligent identification of textures," *Frontiers Neurorobot.*, vol. 6, p. 4, Jun. 2012.
[174] H. Ramakonar, E. A. Franz, and C. R. P. Lind, "The rubber hand illusion and its application to clinical neuroscience," *J. Clin. Neurosci.*, vol. 18, no. 12, pp. 1596–1601, Dec. 2011.
[175] W. W. Lee *et al.*, "A neuro-inspired artificial peripheral nervous system for scalable electronic skins," *Sci. Robot.*, vol. 4, no. 32, 2019, Art. no. eaax2198.

ABOUT THE AUTHORS

Mark M. Iskarous (Member, IEEE) was born in Nashville, TN, USA, in 1993. He received the B.S. degree in electrical engineering and computer science from the University of California at Berkeley, Berkeley, CA, USA, in 2015. He is working toward the Ph.D. degree in biomedical engineering at the Neuroengineering and Biomedical Instrumentation Laboratory, The Johns Hopkins University, Baltimore, MD, USA.

From 2015 to 2017, he was a Hardware Development Engineer with Amazon Lab126, Sunnyvale, CA, where he was working on consumer electronic devices. His current research interests include sensory feedback for upper limb prostheses, neuromorphic models of tactile sensory information, and neuromorphic computing.

Nitish V. Thakor (Life Fellow, IEEE) has been a Professor of biomedical engineering and electrical and computer engineering with The Johns Hopkins University, Baltimore, MD, USA, since 1983. He is currently a Professor of biomedical engineering and the Founding Director of the Singapore Institute for Neurotechnology, National University of Singapore, Singapore. He has authored or coauthored more than 390 refereed journal articles and co-founded three active companies. He holds more than 20 patents. His current research interests include neuroengineering, where he has pioneered many technologies for brain monitoring to prosthetic arms and neuroprosthesis.

Prof. Thakor is a Fellow of the American Institute of Medical and Biological Engineering, Biomedical Engineering Society, and International Federation of Medical and Biological Engineering. He was a recipient of the Research Career Development Award from the National Institutes of Health, a Presidential Young Investigator Award from the National Science Foundation, the Distinguished Alumnus Award from IIT Bombay, Mumbai, India, and a Centennial Medal from the University of Wisconsin School of Engineering.