Sharpness Recognition Based on Synergy between Bio-inspired Nociceptors and Tactile Mechanoreceptors

Adel Parvizi-Fard
https://orcid.org/0000-0002-2205-5083
Nima Salimi-Nezhad
https://orcid.org/0000-0002-4250-0420
Mahmood Amiri (ma_amiri_bme@yahoo.com)
Egidio Falotico
Cecilia Laschi

Method Article

Keywords: Touch sense, E-skin, Nociceptor, Mechanoreceptor, Neuromorphic circuit, Tactile afferents, FPGA

Posted Date: May 26th, 2021

DOI: https://doi.org/10.21203/rs.3.pex-1325/v1

Abstract

Touch and pain sensations are complementary aspects of daily life that convey crucial information about the environment while also providing protection to our body. Technological advancements in prosthesis design and control mechanisms assist amputees to regain lost function but often they have no meaningful tactile feedback or perception. In the present study, we propose a bio-inspired tactile system with a population of 23 digital afferents: 12 RA-I, 6 SA-I, and 5 nociceptors. Indeed, the functional concept of the nociceptor is implemented on the FPGA for the first time. One of the main features of biological tactile afferents is that their distal axon branches in the skin, creating complex receptive fields. Given these physiological observations, the bio-inspired afferents are randomly connected to the several neighboring mechanoreceptors with different weights to form their own receptive field. To test the performance of the proposed neuromorphic chip in sharpness detection, a robotic system with three-degree of freedom equipped with the tactile sensor indents the 3D-printed objects. Spike responses of the biomimetic afferents are then collected for analysis by rate and temporal coding algorithms. In this way, the impact of the innervation mechanism and collaboration of afferents and nociceptors on sharpness recognition are investigated. Our findings suggest that the synergy between sensory afferents and nociceptors conveys more information about tactile stimuli which in turn leads to the robustness of the proposed neuromorphic system against damage to the taxels or afferents. Moreover, it is illustrated that spiking activity of the biomimetic nociceptors is amplified as the sharpness increases which can be considered as a feedback mechanism for prosthesis protection. This neuromorphic approach advances the development of prosthesis to include the sensory feedback and to distinguish innocuous (non-painful) and noxious (painful) stimuli.

Introduction

One of the main functions of the somatosensory system is to respond to the various types of tactile stimuli[1]. Touch sense provides valuable and essential contact information and allows us to interact with the environment and perform daily tasks[2]. Meissner corpuscles, Merkel cells, Ruffini endings, and Pacinian corpuscles are the primary skin mechanoreceptors that transmit tactile information to the upper layers of the nervous system. The Merkel cells and Ruffini endings are labeled as slowly adapting (SA) and respond to the sustained tactile stimuli. Meissner and Pacinian corpuscles which are known as rapidly adapting (RA) mechanoreceptors, respond to the onset and offset of the tactile stimulation[1,3]. These mechanoreceptors are innervated by the first-order neurons of the tactile pathway. The innervation pattern enables individual afferents to encode a portion of the geometric characteristics of the touched objects[4]. More recently, it is demonstrated that tactile information coding[5] and tactile features extraction[4] are also done by fingertip. Indeed, activation of tactile afferents spatially encodes the contact stimuli and sends the tactile information to the upper layers of the somatosensory pathway.

Free nerve endings (nociceptors) are placed in the exterior layer of the skin (epidermal layer) and are widely distributed over the body. They convey the tactile stimuli to the spinal cord leading to the perception of a painful experience[6]. Free nerve endings innervate the skin, bones, muscles, heart, and most of the internal organs. Nociceptors behave as high-threshold mechanoreceptors (HTMR) and respond to harmful stimuli through Aβ, Aδ, and C nerve fibers[3]. The mechanism of pain perception has its own peripheral receptors and includes a complex and chemically unique set of central circuits[7]. It has been demonstrated that painful perception increases when nociceptors are active[7]. In this way, we can perceive a range of innocuous and noxious feelings.

Despite substantial progress in the design and control of prosthesis mechanics[8], sensory perception of prosthetic hands is at the beginning of the road. Due to the importance of the tactile sense and its significant role in prostheses, it has undoubtedly attracted much attention to the development of new tactile sensors and bringing back sensory information in amputees. Recent studies focus on replicating the behavior of biological tactile receptors using sophisticated skin dynamics[9] and neuromorphic systems[10] to improve the efficiency and performance over traditional techniques. The flexible electronic elements[11-13], self-healing [14,15] recyclable materials[16], mechanoreceptor-inspired elements[14,17], and optoelectronic strain sensors[18] have been proposed for prosthetic limbs. In this research, a novel neuromorphic system is designed and then tested by taking into account the biological features of mechanoreceptors and nociceptors for interpretation of tactile information.

Neuromorphic systems replicate the biological functions and spike-based neuronal processing and are broadly based on the analog and digital realization[19]. Neuromorphic sensory systems have made a great step forward in recent years using a new form of asynchronous output representation which provides timing information similar to the action potentials in the biological neuronal system[20]. In the last few years, the application of spiking neural networks and neuromorphic implementations in tactile systems have been increased[10,21-23]. One of the most effective methods of realizing these computational neural models is digital circuit implementation due to their high performance for practical applications[24-30]. Digital execution with Field-Programmable Gate Array (FPGA) offers parallel computations and flexibility for algorithm investigation while filling time and performance limitations. FPGAs have broad applications in the neural network simulations[31] and motivate further exploration[32,33]. An approximate circuit technique was used to implement tactile data processing on FPGA for the e-skin applications[34]. Furthermore, the spiking neural network implemented on FPGA was proposed for bi-directional interaction with living neurons cultured in microelectrode array[35]. The spiking model of cutaneous mechanoreceptor is implemented on the digital hardware (FPGA) to identify the distinct pressure stimuli[36]. For simulation and digital execution of the SA-I and RA-I afferents on the FPGA, the Izhikevich neuron model was frequently used in recent studies due to its rich dynamics which is suitable for tactile sense modeling[36,37]. Salimi-Nezhad and his colleagues[38] implemented a population of afferents on the FPGA to realize the spatial coding and used a glove covered by pressure sensors to recognize objects during grasping. A neuromorphic system for pain perception and self-protection of a hand prosthesis was introduced by

Osborn and his colleagues[37]. They fabricated a multilayered e-skin which imitates the behavioral characteristics of mechanoreceptors and nociceptors to provide sensory feedback for a prosthesis.

Given the fact that the majority of tactile information collected from the environment is encoded not only in multiple sub-modalities but also through a population of different afferent types, in the present research a bio-inspired digital system for the first layer of tactile sensory pathways including SA-I/RA-I afferents and nociceptors is designed. Specifically, the concept of the nociceptor is functionally implemented on the FPGA for the first time. One of the main features of tactile afferents is that their distal axon branches in the skin, creating complex receptive fields[39]. Consequently, the innervation concept to form receptive fields is also integrated into the proposed tactile neuromorphic systems. The digital afferents have receptive fields that overlap with each other. To have a bio-inspired model for the SA-I/RA-I afferents and nociceptor, the Izhikevich neuron model is considered. Moreover, similar to the biological afferents which are not synaptically connected and only convey tactile information from the fingertip to the spinal cord for further processing, here, we have implemented a population of afferent circuits while considering the innervation concept to build receptive fields. Next, we investigate how the collaboration of afferents and nociceptors facilities sharpness recognition. It should be pointed out that utilizing the innervation technique in the prosthetic/robotic applications not only reduces the number of implemented afferents which in turn decreases the cost and power consumption of the neuromorphic devices but also high-resolution tactile sensors can also be handled. Furthermore, by implementing the nociceptors in the proposed tactile neuromorphic system, the concept of pain feeling also emerges. This can provide the prosthesis self-protection to avoid injury during haptic exploration. Indeed, sensor arrays are exposed to damage that can adversely affect the performance of the neuromorphic system[40]. Considering the role of nociceptors and mechanoreceptors, simultaneously, makes the system to be robust against damage in taxels or afferents to some extent. The bio-inspired tactile system includes a population of 23 digital afferents (12 RA-I, 6 SA-I, and 5 nociceptors). Using the proposed system, we explore how the collected spike responses can be used for sharpness classification. In particular, first, the impact of the afferent innervation and creation of receptive field on the firing pattern is investigated. Second, the contribution of tactile afferents and nociceptors on sharpness recognition is explored. Third, the fault tolerance characteristic of the biomimetic system is addressed.

Reagents

1- FPGA (zynq)

2- pressure tactile sensor (Array)

3- microcontroller (Arduino)

4- robotic hand

Equipment

Procedure

1. The human tactile system converts the contact events at the fingertip to trains of action potentials (spikes) and then transmits to upper processing layers. The biological SA-I afferents produce a sustained response to a static indentation of the skin, and the biological RA-I afferents respond only to the onset and offset phases of indentation. Similarly, we have developed a new communication architecture for e-skins that can functionally mimic the behavior of mechanoreceptors and nociceptors.

2. Tactile information is collected from the pressure sensor grid and then transmitted to the neuromorphic system through the interface circuit.

3. A population of 23 afferents (12 RA-I, 6 SA-I, and 5 nociceptors) is digitally realized in the FPGA. The ratio of these two afferents is according to previous research and can be scaled up easily based on the applications.

4. The data which are delivered to the FPGA comes from three groups. Individual digital SA-I afferent receives its inputs directly from the specified receptive field. For each digital RA-I afferent, from its receptive field, the derivative of the input signal is first calculated and then is rectified to be applied to the Izhikevich neuron model. This is due to the fact that based on the biological evidence, the RA-I afferents respond to dynamic skin deformations, hence, for the trapezoidal indentation profile, the RA-I afferents are activated during the onset and offset phases.

5. Individual digital nociceptor also receives the sensor data from all taxels. In this case, we detect the number of taxels (‘*NoT*’) that exceed the predefined thresholds. Next, the maximum current value (‘*MCV*’) of the 25 taxels is determined and then the division of ‘*MCV*’ over ‘*NoT*’ is calculated (shift to the right in the FPGA).

6. Finally, this value is applied to the Izhikevich neuron model to produce spikes. To analyze the tactile data, all 23 obtained spike trains are transmitted to the Personal Computer (PC) through the Universal asynchronous receiver-transmitter (UART) interface.

Troubleshooting

Time Taken

Anticipated Results

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Acknowledgements

The authors would like to thank the esteemed reviewers for their insightful and helpful comments. M. A would like to thank Prof. Nitish Thakor for his valuable discussion. M. A, A. P-F, and N. S-N would like to appreciate Mr. Behnam Rostamian for his assistance in 3D printing and performing the experiments.