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Bio-Inspired Artificial Receptor with Integrated Tactile Sensing and Pain Warning Perceptual Abilities

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Abstract: Inspired by the mechanism of touch and pain in human skin, we integrated two ion-sensing films and a polydimethylsiloxane (PDMS) layer together to achieve a bionic artificial receptor with the capacity of distinguishing touch or pain perception through ion-electrical effect. The ion-sensing film provides the carrier of touch or pain perception, while the PDMS layer as a soft substrate is used to regulate the perception ability of receptor. Through a series of experiments, we investigated the effects of physical properties of the PDMS layer on the sensing ability of an artificial receptor. Further, contact area tests were performed in order to distinguish touch or pain under a sharp object. It is revealed that the pressure threshold triggering the touch and pain feedback of the artificial receptor presented an increasing trend when the elastic modulus and thickness of the PDMS substrate increase. The distinction ability of touch and pain becomes more pronounced under higher elastic modulus and larger thickness. Furthermore, the induced pain feedback becomes more intense with the decrease of the loading area under the same load, and the threshold of pain drops down from 176.68 kPa to 54.57 kPa with the decrease of the radius from 3 mm to 1 mm. This work potentially provides a new strategy for developing electronic skin with tactile sensing and pain warning. The pressure threshold and sensing range can be regulated by changing the physical properties of the middle layer, which would be advantageous to robotics and healthcare fields.

Keywords: IPMC sensor; multifunctional electronic skin; tactile sensing; damage warning; adjustable synthetic artificial receptors; PDMS

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1. Introduction

The unique somatosensory system endows the human body with the ability of somatic function protection and environmental information exchange. Touch and pain are both somatic sensations, which depend on different skin receptors and nerve pathways [1]. The receptors in human skin consist of sensory cells, nerve fibers or free nerve endings that generate stress-strain and space-time electrochemical changes under mechanical load. The action potential caused by the potential difference between the inside and outside of the cell is transmitted to the brain via nerve fibers to complete the transmission of information. Figure 1 depicts the functioning mechanism of the human skin receptor. Separate neurological pathways connect nociceptors and tactile corpuscles to the brain [2]. When mechanical loads are applied to the skin, low threshold mechanoreceptors are partially deformed, which drives the movement of chemical ions (Na^+ and K^+) to produce a potential change in the receptor [3]. This electrical signal is transmitted via nerve fibers to the central nervous system to complete the final expression of tactile information [4]. The nociceptor is currently inactive and will not interfere with the functioning of the tactile receptors. Everyone has a pain sensitivity and tolerance threshold that corresponds to their health status [5]. Specifically, the upper and lower limits of the stimulus field that skin stress tissue can withstand during the perceptual process, as well as sensitivity to even the slightest sensory change within this range. Minimum stimulus and maximum stimulus are the two thresholds of absolute feeling, corresponding to the appearance and disappearance of sensation, respectively. Moreover, the chemical signals induced by external stimuli are transient, whereas the intercellular mechanical signals decay much more slowly than chemical signals, exhibiting rapid conduction and excellent directionality. The coordination of multiple receptors and the nervous system endows the human skin with a unique perception ability including touch and pain, which is crucial to the development of electronic skin. By imitating the structure and functioning mechanism of the somatosensory system [6], multifunctional electronic skins (e-skins) have been constructed. However, the e-skin cannot distinguish normal tactus and pain induced by noxious stimuli [7]. Therefore, it is necessary to investigate the working mechanism of receptors in order to achieve artificial receptors with tactile perception and warning function for injurious stimuli.

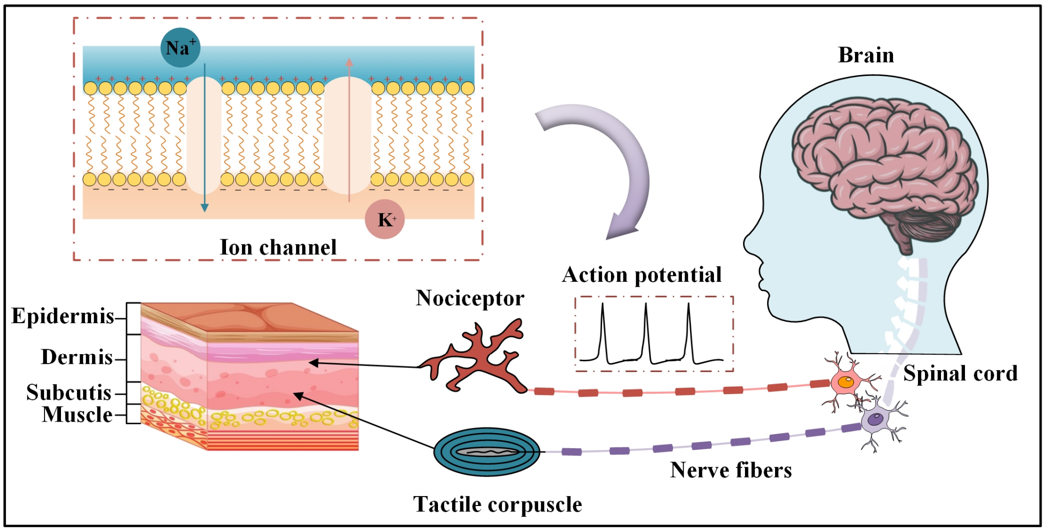

Figure 1. Schematic diagram of the mechanical-electrochemical transduction pathway of the receptor.

Recently, three strategies for the pain-perceptual emulation of e-skin have been proposed. The first strategy is to distinguish innocuous stimuli or noxious stimuli based on a specific threshold. Huang et al., for instance, designed an integrated sensing and warning multifunctional device based on the mechanical and thermal effect of porous graphene, that generate sufficient heating energy to warn the user when the detected signal reaches the threshold condition measured by the ultrasensitive strain sensor [8]. The second strategy is to integrate a tactile sensor with an electrochromic device to achieve physical force sensing and injury visualization [9]. An impressible example was a dual-mode electronic skin inspired by bioluminescent jellyfish that mimics the functions of the mechanoreceptors and nociceptors in the biological skin, respectively, by combining electrical and optical responses to quantify and map gentle tactile and injurious pressure [10]. The third strategy is based on the neural properties of memristors or transistors that mimic the properties of biological synapses [11]. The integration of artificial synaptic devices with pressure sensors permits pain perception and injury detection in the electronic skin. Utilizing the combination of stretchable pressure sensor and memristor [12], Rahman M A et al. built an integrated electronic system to replicate the feedback response of skin receptors and to detect pressure and pain stimuli. These three techniques effectively provide dangerous warnings and trigger the pain. However, unlike the human somatosensory system, current bio-inspired pain-perceptual devices are far from the sensory mechanism of the human body. In recent years, researchers have proposed using ionic polymer materials to imitate the working mechanism (ion migration—electric response) of human receptors [13], including iEAP [14], ionic gel [15] and ionic liquid polymer [16]. By combining such ionic sensing materials, we are able to integrate ionic sensors with a dielectric layer that controls the physical threshold, producing an artificial receptor with dual-mode sensing function. In comparison to sensors coupled with multiple physical signals, it is crucial for the intelligent development of sensors to detect multiple external stimuli through a single signal modality.

Herein, a bio-inspired artificial receptor with bionic-multilayer structure is constructed based on the cooperation between the ionic electrical mechanism of ionic polymer sensors (IPMC layer) and the elastic deformation property of the intermediate substrate (PDMS layer). We analyzed the signal source of the artificial receptor and illustrated its working mechanism by a finite element simulation. The prepared artificial receptor was subjected to a series of increasing force stimuli and its touch and pain sensing properties were evaluated. On the basis of the PDMS layer with varying elastic modulus and thickness, numerous artificial receptors were fabricated. The purpose is to find out the effect of PDMS layer changes on touch/pain-inducing threshold and sensing range to achieve the customized preparation of artificial receptors. To simulate the intense pain sensation caused by sharp objects on human skin, the sensing characteristics of artificial receptors under different contact areas were studied.

2. Materials and Methods

2.1. Materials

The Nafion membrane was purchased from the Dupont company, Wilmington, Delaware, USA. Auxiliary reagents such as $Pd(NH_3)_4Cl_2$, $NaBH_4$, and HCl were obtained from J&K Chemical Inc (Beijing, China). The PDMS films were provided by Hefei Keliao New Material Technology Co., Ltd., Anhui, China. The VHB^{TM} tape (thickness 0.13 mm) was purchased from Minnesota Mining and Manufacturing Corporation company (Shanghai, China).

2.2. Preparation of Receptor

Nafion membrane is widely employed owing to its unique combination of flexible, non-toxicity and ion-exchange properties. The thin metal layer deposits on both sides of the surface of Nafion as electrodes to obtain ion-polymer metal composites (IPMC) with a sandwich structure by chemical or physical methods. In this work, the ionic polymer metal composite (IPMC) films with sensing function were fabricated by immersion reduction plating and electroplating process [17]. Under externally applied pressure, the uneven stress caused by the strain in the IPMC polymer grid drives the cations to migrate to the lower stress region. Then, the subsequent formation of the space charge gradient distribution results in potential difference between the electrodes. Due to the IPMC's internal ion migration and current response characteristics [18], its sensing behavior is similar to that of bioelectrical mechanism. Therefore, IPMC is utilized to replicate the activity of deformed receptors (tactile corpuscles and nociceptors) that generate the action potential when deformed. Inspired by the multilayer structure of human skin, the bio-inspired artificial receptor is constructed of two sensory layers and one flexible PDMS layer, as shown in Figure 2. As sensory layers (thickness 0.2 mm, size 15 mm $\times$ 15 mm), IPMC lies at different depths in the artificial receptor, which is used to receive the mechanical stimuli and convert them into electrical signals. According to the position of the two sensory layers in the structure, we named them as the top IPMC sensory and the bottom IPMC sensory layer, representing the mechanoreceptor and nociceptor, respectively. For each sensory IPMC layer, there are two wires attached to both electrodes, respectively. The PDMS layer (elastic modulus, E = 2.3 MPa, thickness 0.5 mm, size 15 mm $\times$ 15 mm) has excellent chemical stability and low elastic modulus, which serves in three aspects. First, it acts as a supporting layer to position of the top and bottom sensory layers and maintain the overall shape of the artificial receptor; second, the middle layer is involved in the transport and conduction of mechanical stimuli, thereby physically regulating the pressure threshold of artificial receptors; third, the insulating properties of the PDMS layer avoids the crosstalk of two IPMC layers. The presence of VHB^{TM} flexible adhesion layer (thickness

0.13 mm) makes the adhesion between these layers very tight. In addition, the protective layers made of masking tape mirror the biological epidermis to deliver external stimuli and safeguard the interior structure. The size of the encapsulation is larger (30 mm $\times$ 30 mm) than that of the artificial receptor (15 mm $\times$ 15 mm) in order to fix the wires and eliminate interference signals caused by wire movement during testing. Figure S1a shows the front and sectional view of the artificial receptor, as well as the ion sensing film and the PDMS layer constituting the artificial receptor.

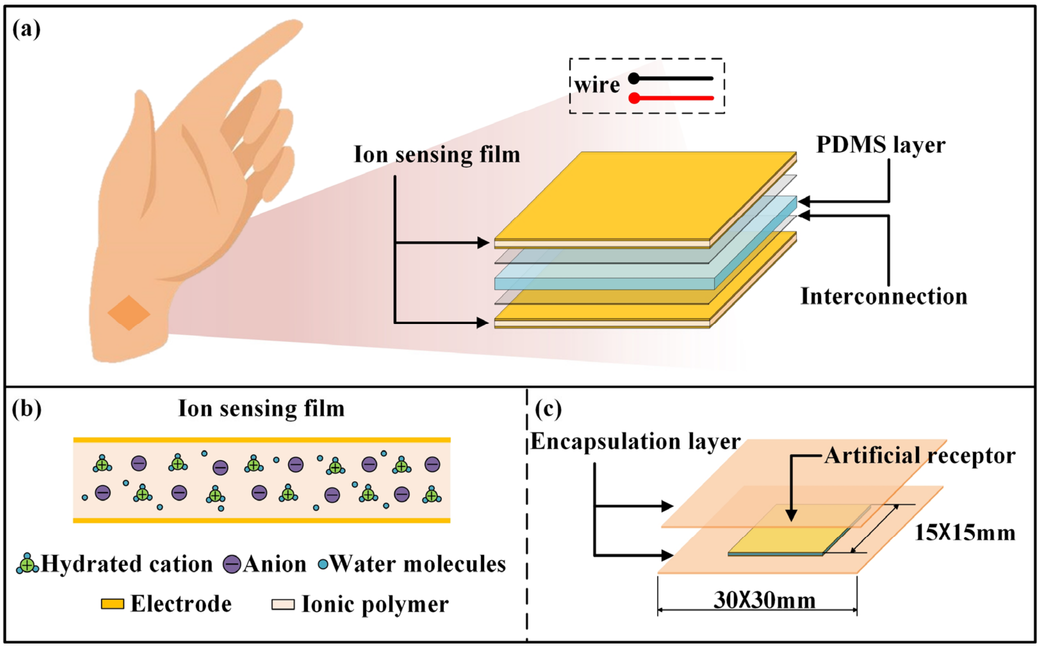

Figure 2. Preparation of bio-inspired artificial receptor. (**a**) Schematic diagram of receptor structure. (**b**) The composition of ion sensing film. (**c**) The encapsulation for receptor.

2.3. Experimental Set-Up

A self-built sensing test platform was used to characterize the sensing performance of a bio-inspired artificial receptor device, which consists of a sample fixing device, a load applying module and a signal processing module, as shown in Figure 3. First, the bio-inspired artificial receptor receives the mechanical stimuli caused by load applying module. Then, the force signal will be converted to the voltage signal via the ion-electric effect of artificial receptor. Third, the electrical signal is transferred to the computing center through signal processing module. By reading the signal, the PC device will recognize the touch or pain perception in real-time. A glass substrate (elastic modulus = 55 GPa) was used to provide the bottom fixation constraint for the artificial receptor. The pressure applied to the artificial receptor was loaded by an applying element fixed on the vibration exciter (SA-JZ002), which controlled by the signal generator (SA-SG030A). A force sensor (ZNLBM-3KG) was mounted at sharker rod to measure the actual force which was applied to the top surface of bio-inspired artificial receptor. A power generator (APS3003S-3D) was used to supply the signal amplification circuit devices with dc voltages. The Labview software on the PC records the voltage generated by the artificial receptor device and the real-time signal of the force sensor using the NI USB-6001 data acquisition.

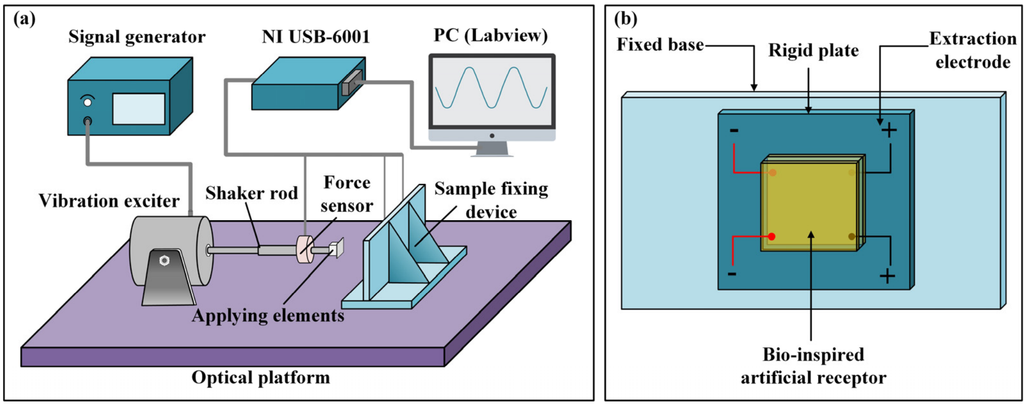

Figure 3. Schematic diagram of test platform for bio-inspired artificial receptor. (**a**) Integral test system. (**b**) The sample fixing device.

3. Results

3.1. Sensing Analysis of the Receptor

The IPMC sensory layer may generate voltage response under compression deformation or bending deformation [19,20]. In order to verify the signal source of the artificial receptor, a series of experiments were implemented on an IPMC sample (thickness 0.2 mm, size 15 mm × 15 mm). The compression load and end displacement applied to the IPMC sample are both sinusoidal signals with a frequency of 1 Hz. The voltage response of the IPMC sample under compression load with different amplitudes are shown in Figure 4a. With the increase of applied pressure, the voltage response signal of IPMC on a rigid substrate shows an increasing trend, but the growth in value is so tiny that it can be ignored. In the bending deformation experiment, a discernible response signal (0.03 mV) is generated even under the displacement load with amplitude of 0.1 mm, which is twice as much as under the compression state of 542.05 kPa (0.015 mV), as shown in Figure 4b. Therefore, it can be confirmed that the sensing signal of the artificial receptor primarily comes from the bending deformation of the IPMC sensory layer, while the voltage response caused by ion migration induced by compression deformation is negligible.

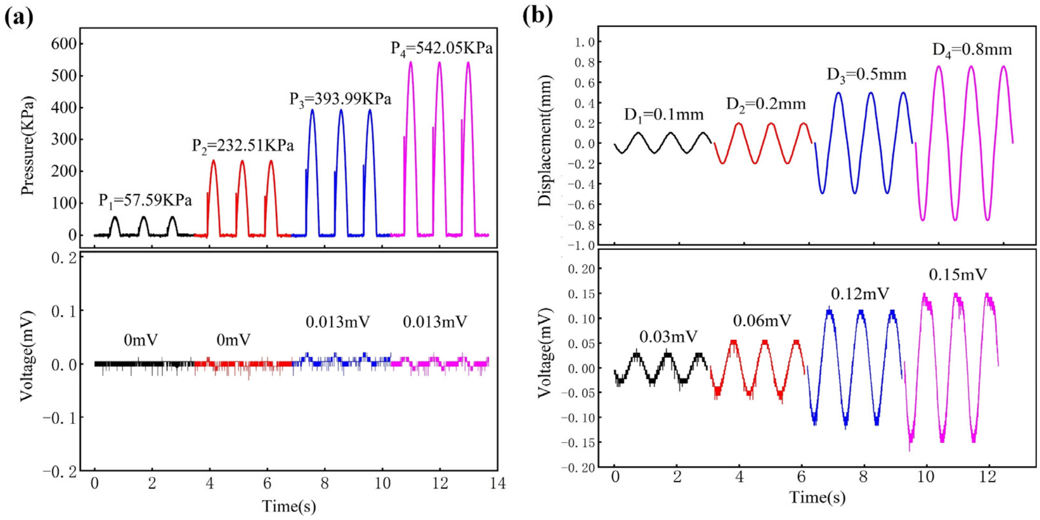

Figure 4. The experimental results of signal source analysis. (**a**) Pressure−applying signal and voltage response of IPMC sensing layer in compression mode. (**b**) Displacement−applying signal and voltage response of IPMC sensing layer in bending mode.

To theoretically analyze the working mechanism of the bio-inspired artificial receptor, we implement finite element simulations. The material characteristic parameters are shown in Table S1. Finite element mesh types use automatic meshing, as shown in Figure S2. The artificial receptor undergoes two operating modes under different load stimuli, which were applied to a circular loading region with a radius of 3 mm, as shown in Figure 5a. Figure 5b shows the deformation distributions of the top sensory layer, the PDMS layer and the bottom sensory layer. The deformation of each layer, from top to bottom, is 0.036 mm, 0.029 mm, and 0.007 mm when the pressure is 106.01 kPa. The deformation of the bottom sensory layer is only one-fifth that of the top, which is also less than the top sensory layer's deformation at 35.33 kPa (0.012 mm). Consequently, only the top IPMC layer and the PDMS layer are under compressive stress state. At this point, the top IPMC sensory layer is active while the bottom IPMC sensory layer is inactive, thus the working mode of the whole artificial receptor is tactile perception state. With the increase of applied load, mechanical signals can break through the physical threshold of the PDMS layer and transfer to the bottom IPMC layer. Figure 5c shows the deformation distributions of three layers at 353.36 kPa. The deformation of the bottom sensory layer reaches 0.024 mm, indicating that the working mode of the entire artificial receptor is nocuous perception state. In addition, the stress on each layer is relatively uniform, and the shape of the deformation area matches that of the loading area. Maximum stress is observed at the contact edge between the pressing element and the sensory layer, and it attenuates from close to far along the direction of load application. Taking into account the stress state, the IPMC electro-mechanical coupling mechanism and circuit connection, we can estimate that the output voltage of the two sensory layers will remain comparable and that the signal of the IPMC layer at the top will be stronger.

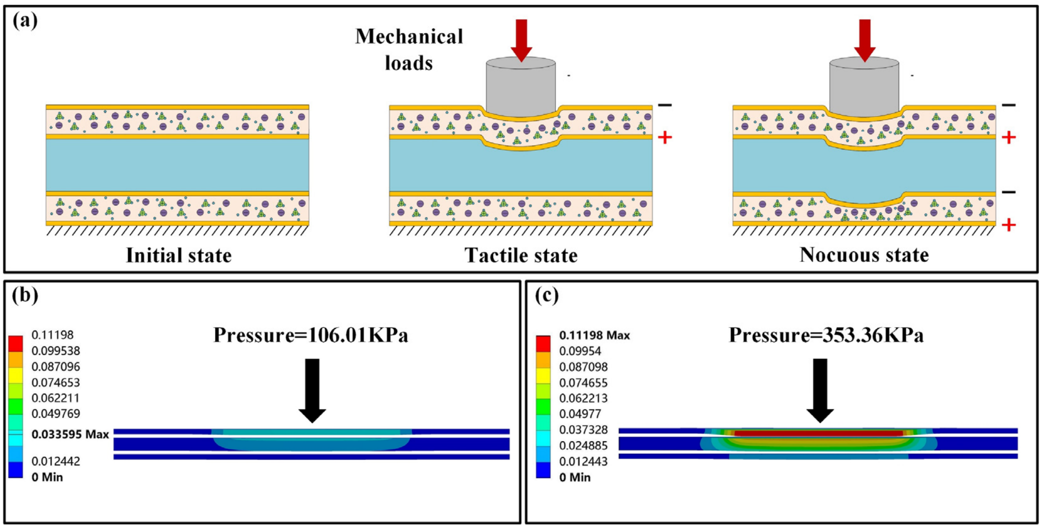

Figure 5. Working mechanism of the bio−inspired artificial receptor under mechanical stimuli with different amplitude. (**a**) Schematic of bio−inspired artificial receptor in different phases of operation. (**b**) The deformation distribution cloud diagram of the top IPMC layer, PDMS layer and bottom IPMC layer when load is 106.01 kPa. (**c**) The deformation distribution cloud diagram of the top IPMC layer, PDMS layer and bottom IPMC layer when load is 353.36 kPa.

3.2. Characterization of Touch and Pain

Our bionic artificial receptor can measure and discriminate touch or pain based on the voltage response induced by pressure stimuli. We evaluate the receptor's reaction to touch stimuli with different pressure amplitudes from 70.67 kPa to 176.68 kPa. As shown in Figure 6a, the top IPMC sensory layer presents increasing voltage response signals (0.0064 mV to 0.0148 mV) with the increase of the loading force amplitude. A large pressure corresponds to the large output voltage in the top sensory layer, while the bottom IPMC sensory layer has no response signals, which can be attributed to the PDMS layer absorbing all the energy. At a frequency of 1 Hz, Figure 6b shows the observed output voltage with different normal force amplitudes. With the increase of pressure from 247.35 kPa to 459.36 kPa, the bottom IPMC sensory layer begins to generate response signals and keep an upward trend to 0.0086 mV. In the real-time waveform of the output voltage, the phase of the two sensory layers is equal, validating the prediction of the prior finite element simulation. Besides, it can be observed that the signal of the top IPMC sensory layer is larger due to the static attenuation in the PDMS layer. Figure 6c presents the amplitude voltage value of top and bottom sensory IPMC layers under a series of increasing pressures. According to different pressure thresholds, the sensing range is defined as non-perceptual area, tactile sensing area and pain sensing area, which shows obvious differences among all regions. As shown in Figure 6d, the artificial receptor shows great linearity, with tactile sensitivity and pain sensitivity of 0.136 mV/Pa and 0.026 mV/Pa, respectively. The difference in the sensitivity for both sensory layers is attributed to the PDMS layer since the top sensory layer absorbs more deformation from external stimuli. Figure S1b shows the sensing signals of an artificial receptor at 176.68 kPa and 371.02 kPa. The experimental results are consistent with the experimental results in the paper.

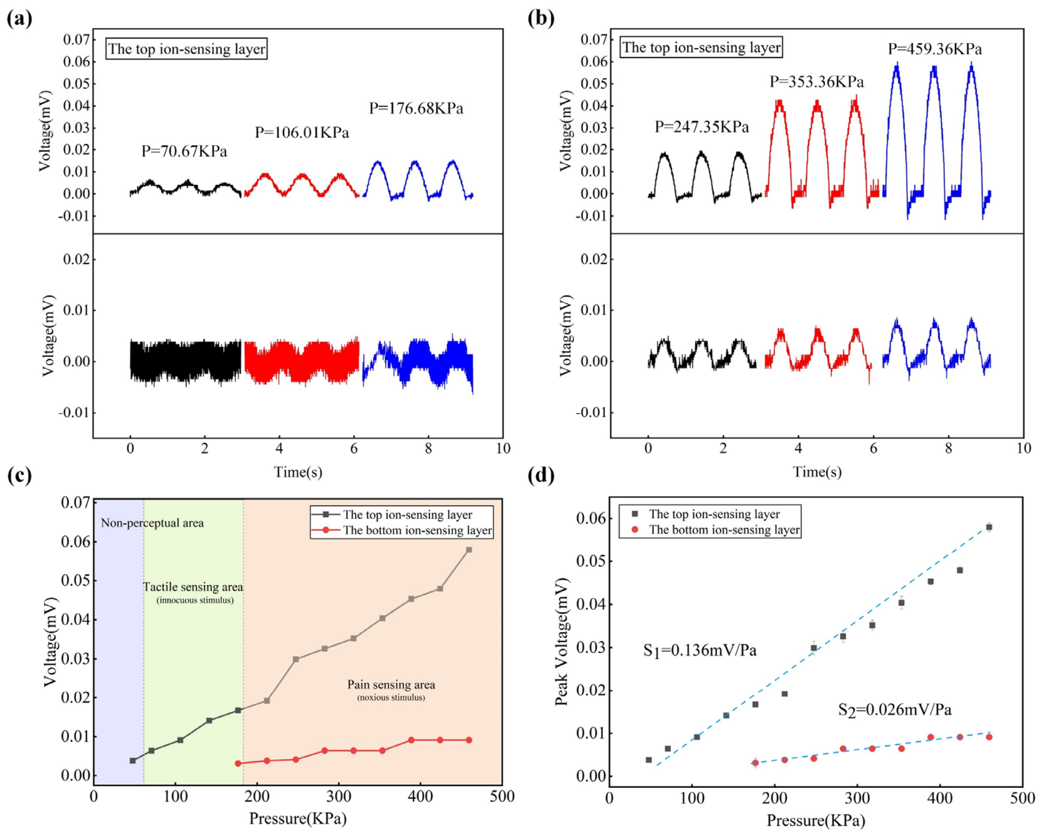

Figure 6. Experimental results of the bio−inspired artificial receptor. (**a**,**b**) Real−time waveform of the output voltage under different normal force amplitudes with a frequency of 1 Hz. (**c**) The voltage response with the increase of pressure shows different sensing modes in different pressure ranges. (**d**) Sensitivities of the bio−inspired artificial receptor during the pressure from 0 to 500 kPa.

3.3. PDMS Layer Effects

Since the permissible range of skin stimuli is governed by the threshold of pain perception, minute changes in skin structure and the distribution of receptors can affect the threshold that controls the transmission of pain signal. We investigated the effect of the elastic modulus and thickness of the PDMS layer on the sensing property of bio-inspired artificial receptor. The trend in Figure 7a represents the output voltage of artificial receptors with different elastic moduli PDMS layers under the same loading condition (353.36 kPa). With the elasticity modulus of the PDMS layer varying from 2.3 MPa to 1.2 MPa, the output voltage of bottom sensory layer changes from 0.0068 mV to 0.0579 mV, as well the voltage response of the top sensory layer increases from 0.043 mV to 0.132 mV. The increased elastic modulus of the PDMS layer will result in a stiffer structure, reducing the deformation and voltage response of the bottom sensory layers. The sensing ability of biomimetic artificial receptors assembled with PDMS layers of varying elastic modulus are shown in Figure 7b. As the elastic modulus decreases, the tactile perception range (green safety area) gradually decreases while the pain perception range (orange warning area) increases persistently. It indicates that a smaller loading force can trigger pain feedback of artificial receptors assembled by the PDMS layer with lower elastic modulus. Another discovery is that the two sensory layers have the higher voltage response when the thickness of the PDMS layer decreases. The trend in Figure 7d shows the output voltage of artificial receptors with different PDMS layers thickness under the same loading condition (353.36 kPa). The output voltage of the bottom sensory layer shows a downward trend from 0.0100 mV to 0.0035 mV with the thickness of the PDMS layer increasing from 0.1 mm to 0.7 mm, as well the output voltage of the top sensory layer changes identically as that of the bottom layer. Under the same pressure load (353.36 kPa), the deformation of bottom sensory layer behind the thicker PDMS layer is slightly lower due to the mechanical signal attenuation caused by the stiffer, thicker PDMS layer. The sensing ability of biomimetic artificial receptors assembled by PDMS layers with different thickness are shown in Figure 7e. The results indicate that the tactile sensing range reduces as the PDMS thickness decreases, while the pain sensing range has an opposite tendency. To verify the customizability of artificial receptors, we further determined the relations of the pressure threshold to physical properties of the PDMS layer using the experimental results. As the thickness increases, the pressure threshold that triggers pain increases from 70.67 kPa to 212.01 kPa, while the induced touch pressure threshold shows a small increase, as shown in Figure 7f. It can be attributed to the anabatic loss of mechanical force in the thicker PDMS layer, which makes it difficult for the bottom sensory layer to generate a voltage response at lower pressures. Similarly, with the increase of elastic modulus from 1.2 MPa to 2.3 MPa, the induced pain pressure threshold rises from 43.2 kPa to 176.68 kPa, while the tactile pressure threshold did not change significantly (Figure 7c). In addition, it can be concluded that the distinction ability of touch or pain signals becomes more obvious as the elastic modulus and thickness of the PDMS layer rise. The above results indicate that the activation of the tactile perception mode of artificial receptors is strongly correlated with the external stimulus load and the PDMS layer thickness. The pattern of pain perception is affected by both external stimuli and the PDMS layer. Therefore, the pain perception of artificial receptors can be regulated by changing the physical properties of middle layer, thus achieving the customization of the perception range.

3.4. Contract Area Effects

Typically, the human body receives pain information from acute touch with a tiny contact area. We altered the loading area of the artificial receptor and carried out a series of comparative experiments. Figure 8a shows the voltage response of artificial receptors under different loading regions at 353.36 kPa. The experimental results indicates that the output voltage of the top IPMC sensory layer falls and then increases when the radius of the applied element reduces from 3 mm to 1 mm. The sudden decrease of tactile response at R = 2 mm is attributed to the offset effect of compressive deformation in the contact area and bending deformation at the contact edge resulting from the presence of a flexible PDMS substrate [21]. As for the bottom IPMC sensory layer close to the rigid substrate, the smaller contact area causes a larger stress distribution on the surface of the artificial receptor, which increases the deformation of the whole structure along the loading direction and the output voltage of the pain response. The output peak voltage of the bottom IPMC layer representing pain perception steadily increases with the decrease of the loading area, which indicates that a smaller loading force can trigger pain perception, as shown in Figure 8b. Both the induced touch and pain threshold of artificial receptors show a descending trend gradually with the decrease of the loading area, which well simulated the intense pain of biological skin hit by a sharp object. Due to the proximity of the top sensory layer to external stimuli and the thinness of the protective masking tape layer, the metal electrode surface of the top sensory layer suffers damage after extended cycles under the minimum-area pressing element, while that of the bottom sensory layer is still intact due to the protection of thick PDMS layer. It is worth noting that this novel multiplayer dual functional sensor can be operated bi-directionally along the out-of-plane axis, i.e., it will work the same way when the device is flipped over (the bottom layer becomes the top layer).

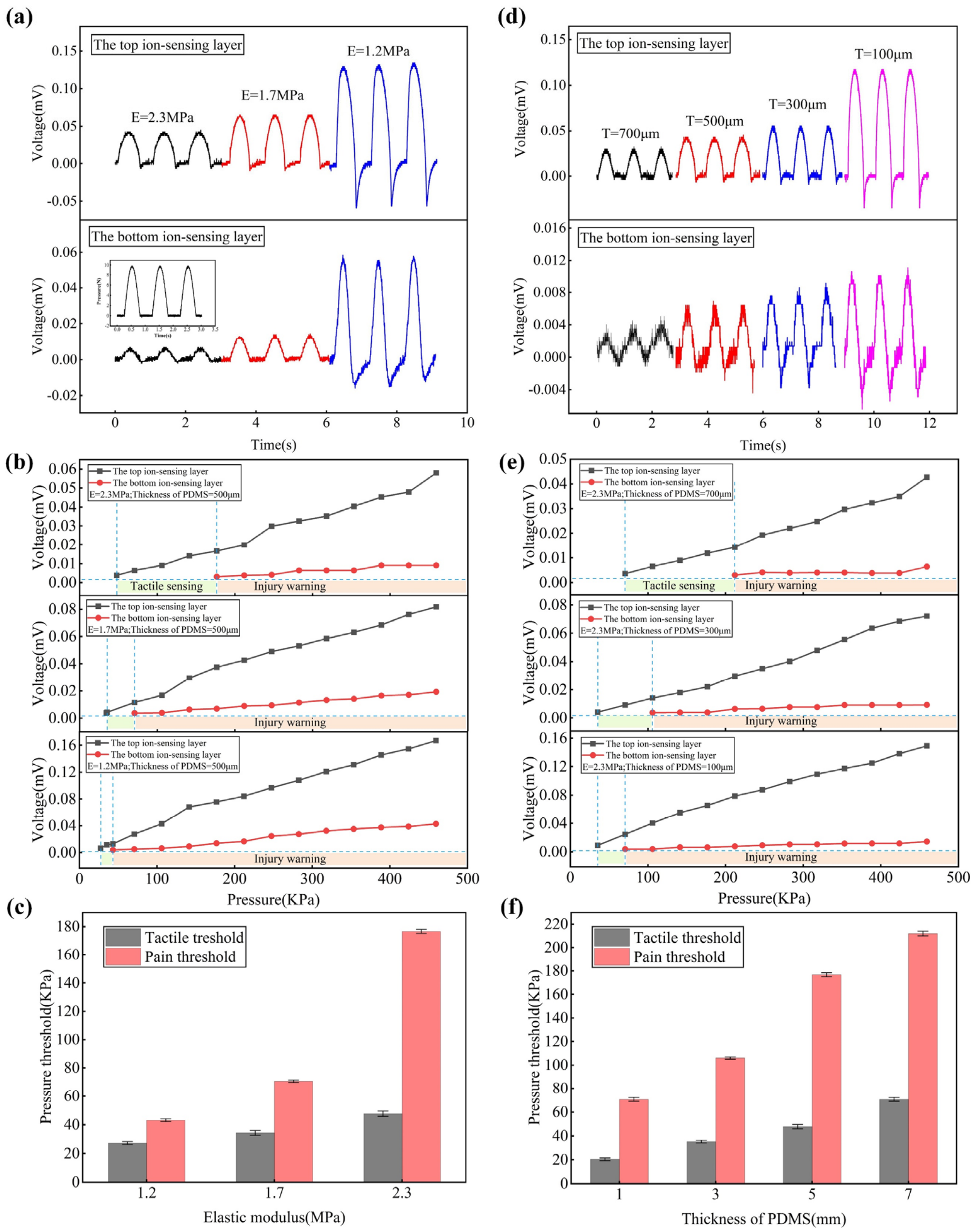

Figure 7. The experimental results. (**a**) Effect of PDMS layer with different elastic modulus on voltage response of artificial receptor. (**b**) The tactile/pain−sensing range of artificial receptors with change of PDMS elastic modulus. (**c**) The induced touch/pain threshold changes with different elastic moduli of PDMS layer. (**d**) Effect of PDMS layer with different thickness on voltage response of artificial receptor. (**e**) The tactile/pain−sensing range of artificial receptors with change of PDMS thickness. (**f**) The induced touch/pain threshold changes with different thicknesses of PDMS layer.

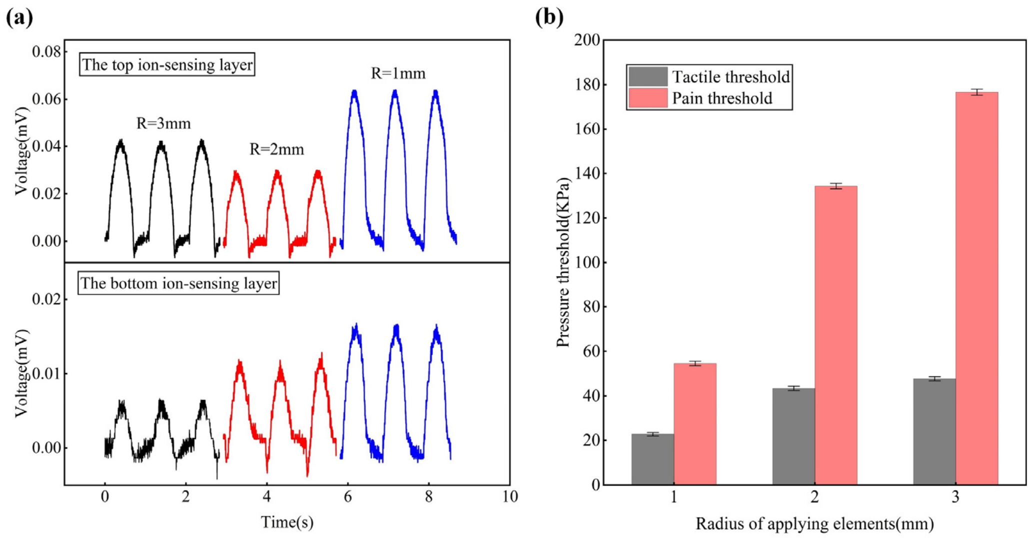

Figure 8. The experimental results. (**a**) Effect of applying elements with different radius on voltage response of artificial receptor. (**b**) The pressure threshold of artificial receptors when the radius of the contact circle increases from 1 mm to 3 mm.

4. Discussion

In this work, we report a bio-inspired artificial receptor with innocuous sensing and damage warning functions based on the coordination of ion-electric response principle and mechanical signal attenuation, which simplifies manufacturing and signal decoupling. The sensing voltage of artificial receptor primarily comes from the bending deformation of two IPMC sensory layers. According to the finite element simulation and experiments, the artificial receptor includes three operating states: non-perceptual state; tactile sensing state; and pain sensing state. The sensitivity of the touch response and pain response is 0.136 mV/Pa and 0.026 mV/Pa, respectively. Further, the pressure threshold that triggers touch and pain can be adjusted by changing the physical properties of the PDMS layer. As the PDMS thickness increases from 0.1 mm to 0.7 mm, the induced pain pressure threshold rises from 70.67 kPa to 212.01 kPa, while the induced touch pressure threshold shows a small increase from 20.46 kPa to 70.67 kPa. Similarly, the induced pain threshold increases from 43.20 kPa to 176.68 kPa with the growth of PDMS elastic modulus from 1.2 MPa to 2.3 MPa, and the induced touch threshold changes from 27.29 kPa to 47.75 kPa. The excellent performance tunability will greatly facilitate the customizable fabrication of artificial receptors. More than that, the threshold of pain drops down from 176.68 kPa to 54.57 kPa with the decrease of the radius from 3 mm to 1 mm, indicating that the artificial receptor can imitate the pain of skin in response to a sharp touch. The proposed artificial receptor with the capability of pain perception in our work will be beneficial to many fields, including electronic skins, robotics, healthcare and so on.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/machines10110968/s1, Figure S1: (a) The materials, front view and sectional view of artificial receptor (b) The pressure test experiments of artificial receptor; Figure S2: Schematic diagram of grid division; Table S1: Material characteristic parameter.

Author Contributions: Conceptualization, X.Z. and G.T.; methodology, X.Z. and Y.J.; writing—original draft preparation, X.Z.; writing—review and editing: G.T., C.X., L.L., B.L. and Y.W.; supervision, C.Z. and D.M.; project administration, Y.W. All authors have read and agreed to the published version of the manuscript.

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