

## SENSORS

# A biomimetic elastomeric robot skin using electrical impedance and acoustic tomography for tactile sensing

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Human skin perceives physical stimuli applied to the body and mitigates the risk of physical interaction through its soft and resilient mechanical properties. Social robots would benefit from whole-body robotic skin (or tactile sensors) resembling human skin in realizing a safe, intuitive, and contact-rich human-robot interaction. However, existing soft tactile sensors show several drawbacks (complex structure, poor scalability, and fragility), which limit their application in whole-body robotic skin. Here, we introduce biomimetic robotic skin based on hydrogel-elastomer hybrids and tomographic imaging. The developed skin consists of a tough hydrogel and a silicone elastomer forming a skin-inspired multilayer structure, achieving sufficient softness and resilience for protection. The sensor structure can also be easily repaired with adhesives even after severe damage (incision). For multimodal tactile sensation, electrodes and microphones are deployed in the sensor structure to measure local resistance changes and vibration due to touch. The ionic hydrogel layer is deformed owing to an external force, and the resulting local conductivity changes are measured via electrodes. The microphones also detect the vibration generated from touch to determine the location and type of dynamic tactile stimuli. The measurement data are then converted into multimodal tactile information through tomographic imaging and deep neural networks. We further implement a sensorized cosmetic prosthesis, demonstrating that our design could be used to implement deformable or complex-shaped robotic skin.

## INTRODUCTION

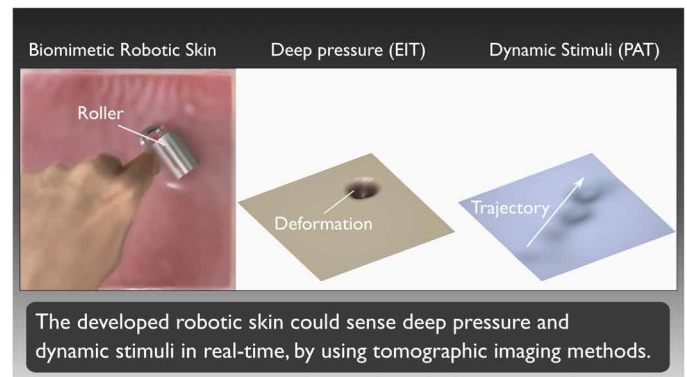
Human skin has inspired the creation of robotic skin because it has various beneficial features for physical human-robot interaction (pHRI) environments. Human skin is the largest sensory organ, with an area of about 2 m<sup>2</sup>, protecting our entire body from external influences (1). The skin has four types of mechanoreceptors to feel various tactile stimuli (2, 3). Also, human skin efficiently achieves large-area tactile sensing capability using cognitive processing and a few mechanoreceptors that have a large receptive field (4, 5). If there is a robotic skin replicating these unique features, it would allow the robot to interact with the environment like humans. Integrating these features in a single robotic skin system is challenging, but it will be substantially beneficial for future robotics in pHRI environments.

Many robotic skin systems have been introduced since tactile sensing has become an important issue for humanoids (6, 7), prostheses (8, 9), and social robots (10, 11). Most systems primarily focus on protection and large-area sensing functionalities. The most common approach has been the use of two perpendicular and stretchable electrode lines (row and column electrodes) to form an array of sensing elements where each intersection of row and column electrodes forms a single tactile sensor (12–14). This approach can achieve a large sensing area with a small number of electrodes, but practical limitations—such as fabrication complexity for a large and three-dimensional (3D) geometry, fragility, complex wiring, and repair difficulties—still need to be addressed. Another widely adopted approach has been the use of microcontrollers and digital communication to modularize the sensing elements (15, 16).

These module-based robotic skins can achieve high scalability and robustness by connecting each module via a serial bus and monitoring their functionality, but fragile wiring exposed to the outside and relatively large power consumption (about 30 mW/cm<sup>2</sup>) are considered to be their major drawbacks (16).

Alternatively, Lee *et al.* reported a neuromimetic architecture that enables simultaneous transmission of thermotactile information through a single conductive material. This method also allows the robotic skin to achieve a scalable and damage-resilient structure (17). There are other approaches implementing large-area sensing functionality using stereo cameras (18) or accelerometers (19), but fulfilling these aforementioned features of human skin (protection, multimodal sensing, and scalability) has not been achieved, especially in terms of practical requirements such as durability, cost efficiency, and repairability.

Here, we report a biomimetic robotic skin based on hydrogel-elastomer hybrids and tomographic imaging (Movie 1). The goal of our work was to provide a robot with human skin-like features



Movie 1. Summary of study.

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such as protection, multimodal tactile sensation, high scalability, and reparability. The developed robotic skin has a skin-inspired multilayer structure that consists of an ionic hydrogel and a silicone elastomer. The physical properties of the hydrogel are customizable and can be further improved through integration with silicone. The synergy between hydrogel and silicone allows the robotic skin to achieve not only skin-like softness but also high resilience for protection. The robotic skin can detect resistance changes and vibration using electrodes and microphones. These measurement data are subsequently used to reconstruct multimodal tactile sensation through tomographic imaging with the use of electrical impedance tomography (EIT) (20, 21) and passive acoustic tomography (PAT) (19, 22). Deep neural networks (DNNs) are also used to improve the reconstruction performance or to classify the touch modality based on vibration signals. The robotic skin is also robust to external impact because there is no wire inside the multilayer structure. Furthermore, we demonstrated that the tactile sensing capability can be easily restored even after incisional damage (23). By combining the multilayer structure and tomographic imaging, we developed a robotic skin that resembles human skin in structure, function, and working principle. We further implemented a sensorized cosmetic prosthesis to demonstrate the potential of the proposed robotic skin.

## RESULTS

### Biomimetic multilayer structure with distributed sensing elements

Human skin is composed of three primary layers (epidermis, dermis, and hypodermis), which have different characteristics and functions. The epidermis is the outermost layer of the skin that forms a waterproof barrier to prevent dehydration. The epidermis layer has a Young's modulus of about 2 MPa, which is considerably high (24). The dermis is an elastic layer that lies beneath the epidermis. This layer consists of elastic tissue and fibers, giving skin resilience and toughness. The reticular dermis can be stretched up to 25% owing to the collagen fibers that ensure full recovery of tissue shape and structure after deformation (25). The dermis is physically interlocked with the epidermis, so they are not sliding over each other even under the shear force. It also creates a spatial filtering effect that spreads forces and pressure across a large area (26, 27). Last, the hypodermis (also called subcutaneous layer) is a thick and highly deformable layer found between the dermis and fascia. The hypodermis mainly consists of soft loose connective tissues (areolar tissue and adipose tissue), and their mechanical properties allow the skin to efficiently absorb and attenuate external pressure. Although it is not a part of skin, its structure and function are closely related to those of the dermis. Four primary tactile mechanoreceptors are also located in different layers in human skin. Merkel's disks and Meissner's corpuscles are located toward the surface of the skin. Ruffini endings and Pacinian corpuscles are located deeper inside the skin (28); they are often found in deep fascia, which is located beneath the hypodermis (29, 30).

Inspired by the structure of human skin, we create a biomimetic robotic skin consisting of four parts: elastomeric skin, a hydrogel layer, a base layer, and distributed sensing elements (Fig. 1A). The outermost layer of the sensor is elastomeric skin, which is made of stretchable and tough silicone rubber. The hydrogel layer is a compliant layer located underneath the elastomeric skin. The base layer

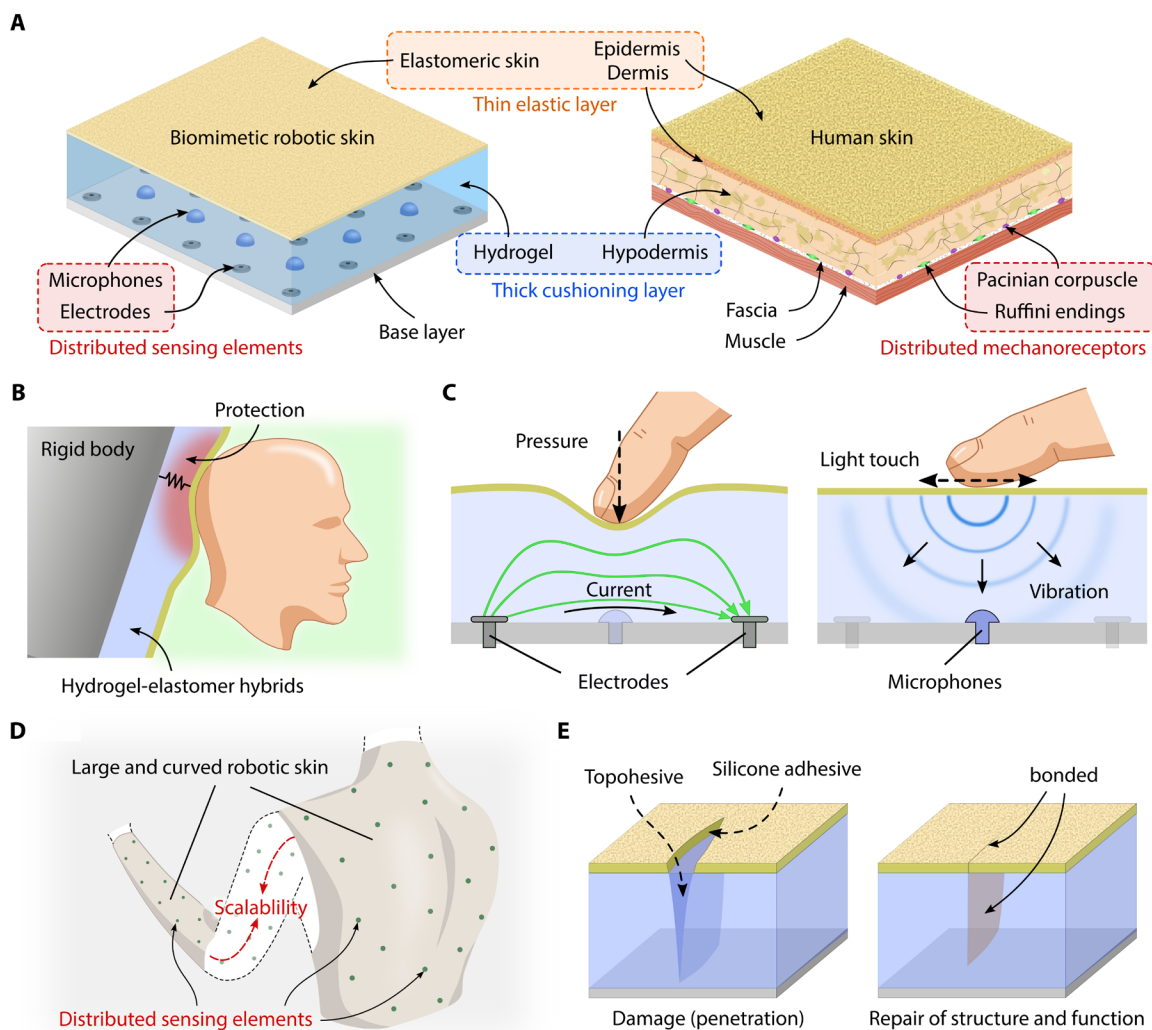
is a flexible plate coated with silicone rubber, and it is placed below the other layers to support them. These three layers are strongly cross-linked to each other so that those layers are not delaminated during physical interaction (31). For multimodal tactile sensing, the electrodes and microphones are placed between the base layer and the hydrogel layer. We use this configuration to replicate some beneficial features of human mechanoreceptors.

The proposed structure offers several advantages for robotic skin. First, the robotic skin would have a protective function for safe human-robot collaboration, owing to the mechanical properties of the hydrogel-elastomer hybrids (Fig. 1B). The multilayer structure has a spatial filtering effect that offers a cushioning function of the skin. The compliance of the hydrogel provides a dampening effect from external force, whereas the elastomeric skin withstands the force and spreads it to a larger area (fig. S1). In addition, we can customize the geometries and/or mechanical properties of the multilayer structure to achieve an appropriate elastic modulus and thickness of the robotic skin; it would enable the robotic skin to fulfill safety criteria for various injuries, such as contusion (energy density,  $<2.52 \text{ J/cm}^2$ ) and laceration (tensile stress,  $<1 \text{ MPa}$ ) (32). If the sensor is made only with the hydrogel, then deformation occurs locally in a small area so the sensor would not offer a sufficient protection. Because this protective function is realized by the mechanical properties of the multilayer structure, it is not impaired by the sensing characteristics (sensitivity and bandwidth). In addition, the elastomeric skin prevents direct contact between the hydrogel and air, offering an antidehydration effect. Specifically, the elastomeric skin effectively mitigated moisture loss of the hydrogel (fig. S2) over 60 days without noticeable changes in sensing performance or the need of retraining in machine learning algorithm. The long-term stability of the system can potentially be improved by the use of elastomers with much lower water permeability, such as butyl rubber (33) and/or nonvolatile ionic hydrogels (34).

The hydrogel layer can also be used as a medium for tactile sensing (Fig. 1C). Hydrogels contain a large amount of water and have electrical conductivity because of the presence of electrolytes (fig. S3) (35). We also demonstrated that hydrogels transmit the vibration generated by touching the surface to the entire multilayer structure. These properties allow us to deploy electrodes and microphones on the base layer and use them to measure the force and vibration applied to the sensor's surface. The developed robotic skin is able to detect not only weak vibrations but also forces up to 20 N (figs. S4 and S15), which is sufficient to sense typical human touch interaction such as a stroke or push (36).

The distributed sensing elements allow the robotic skin to achieve high scalability (Fig. 1D). Each sensing element has a large receptive field so that the robotic skin can achieve a large sensing area with a small number of sensing elements. In addition, the sensing elements can be freely arranged within a large, curved, and even deformable surface. Because there is no direct connection between the sensing elements, we can incorporate an additional sensing element without concern about the existing sensing elements. This feature allows us to easily adjust the size of the robotic skin.

In addition, the robotic skin has the ability to repair after damage without loss of its functionality (Fig. 1E). If excessive force is applied to the robotic skin, the multilayer structure may become locally lacerated or crushed, causing the robot skin to lose its sense of touch. The proposed design does not expose any wires, whereas other approaches expose wires or circuits externally. We have



**Fig. 1. Concept of biomimetic multilayer structure for robotic skin.** (A) Comparison between the biomimetic multilayer structure based on hydrogel-elastomer hybrids and human skin. Both structures consist of an elastic and tough outermost layer (elastomeric skin and dermal layer) and a thick and compliant cushioning layer (hydrogel and hypodermis). Sensing elements were also evenly distributed deep in the multilayer structure. (B) The multilayer structure allows the robotic skin to achieve an appropriate material property and dimensions for the protection function. (C) Because the hydrogel layer is compliant and electrically conductive, it can be used as a pressure-sensitive material. In addition, dynamic tactile stimuli (light touch) can be measured by detecting vibrations generated on the surface and transmitted through the multilayer structure. (D) Scalable design based on distributed sensing elements with a large and overlapping receptive field. (E) The biomimetic robotic skin can be repaired with an adhesive after damage to restore its structure and function.

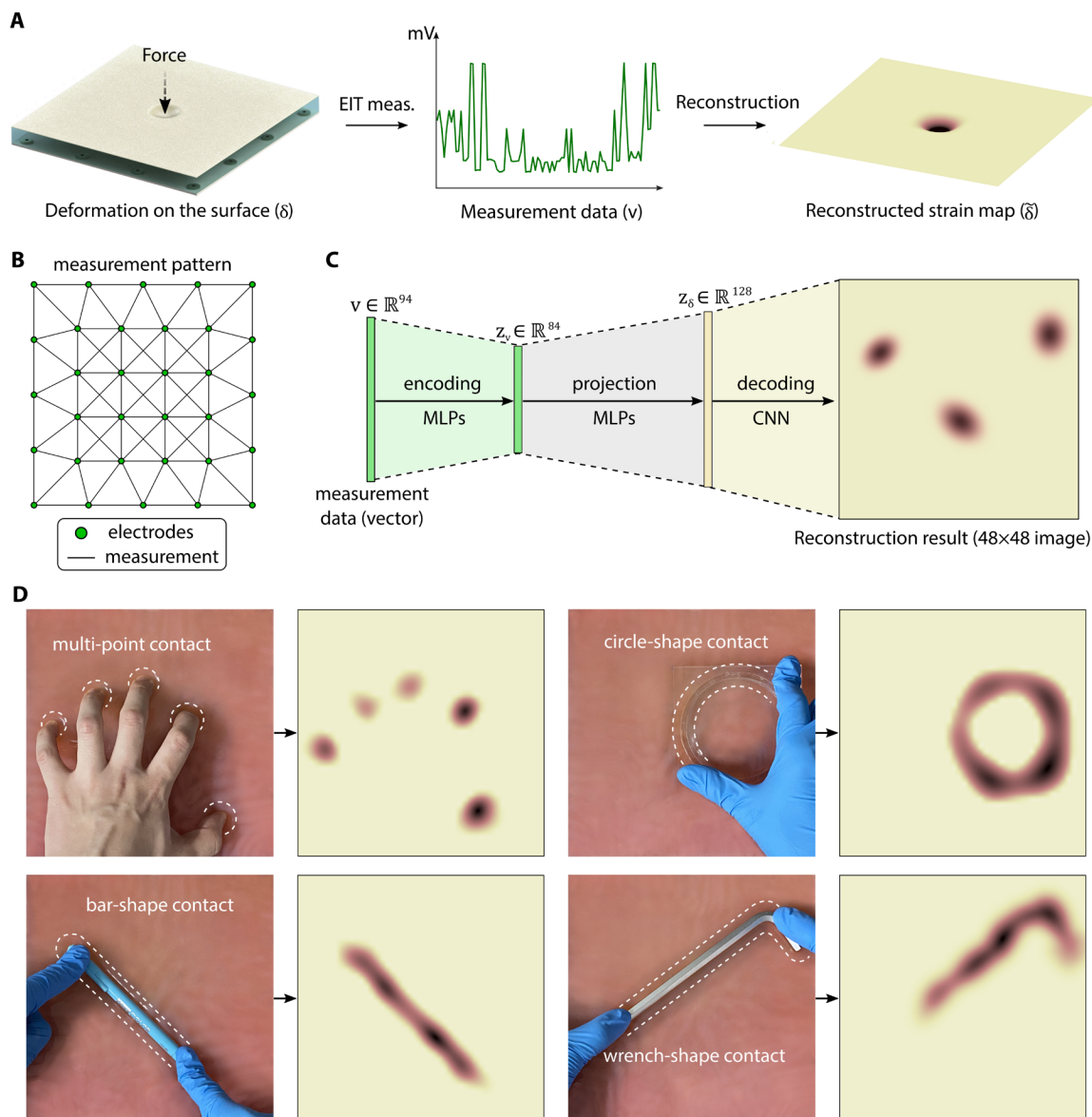
demonstrated that the robotic skin is repairable by restoring the electrical and mechanical properties of the multilayer structure using an adhesive for hydrogel or silicone rubber (37, 38).

### Deep pressure sensing based on EIT

To sense deep pressure, we used the hydrogel as a pressure-sensitive material. The hydrogel is electrically conductive, and it is deformed when a force is applied. The impedance between electrodes was altered depending on the cross-sectional area for current to flow, which was reduced due to indentation. The results showed that the electrical impedance increased proportionally to the indentation depth (fig. S4). There was no dead zone, and the limit of detection was about 0.7 N. Hydrogels also exhibit low piezoresistive hysteresis (less than 3%) because the piezoresistive mechanism is based on

changes in geometry (cross-sectional area for current flow) rather than changes in the percolation network (39).

Because the pressure was locally applied to the robotic skin, the conductivity distribution of the hydrogel was found to be locally altered accordingly. The location and intensity of the deformation can be observed using EIT, a nondestructive imaging technique that has been widely used for medical imaging (40, 41), geophysical exploration (42), and human-machine interfaces (43, 44). Figure 2 demonstrates how the proposed robotic skin senses deep pressure using EIT. The metal electrodes were evenly placed between the hydrogel and the base layer, so the local deformation of the thick hydrogel layer can be indirectly measured using the electrodes (Fig. 2A). An alternating current of 40 kHz was injected through a pair of electrodes, and the resulting voltage was measured across



**Fig. 2. Deep pressure sensing using EIT.** (A) Sensing procedure for deep pressure using EIT. The measurements were conducted across the electrodes, and these data were used to reconstruct the deformation map due to deep pressure. (B) Optimal measurement pattern for the developed robotic skin. The green circles and black lines indicate the electrodes and measurement pair, respectively. The electrode arrangement was heuristically determined so that 32 electrodes were spaced as evenly as possible in a square area. (C) Deformation map was reconstructed from measurement data through DNN-based EIT algorithm. (D) Image reconstruction results for various shapes of deep pressure (multipoint contact, circle-shaped contact, bar-shaped contact, and wrench-shaped contact).

that pair. We used an alternating current to minimize the double-layer capacitance at the interface between the electrodes and electrolyte (45). The measurements were then repeated on other pairs of electrodes along the predefined measurement pattern (Fig. 2B). Last, the measurement data were converted into a deformation map using an EIT reconstruction algorithm.

There are various inverse solving algorithms for implementing EIT (46, 47), but most of them have a trade-off between accuracy and speed (text S1). Thus, we used an EIT reconstruction algorithm based on a DNN, which has shown promising results in terms of accuracy, noise robustness, and reconstruction speed (Fig. 2C and fig. S6) (48, 49). In this method, a measurement vector was mapped

into the latent variable through multilayer perceptron (MLP), and a deformation map was generated from the latent variable through a convolutional neural network (CNN). The network was trained using simulation data because it is impractical to obtain measurement data by experiments.

To demonstrate the EIT reconstruction performance, we pressed the biomimetic robotic skin with a hand or objects of various shapes and obtained the reconstruction results through the DNN-based EIT algorithm (Fig. 2D and movie S1). The result shows that the trained network can reconstruct deformation maps of various shapes. This result is notable considering that the spacing of the electrodes is about 40 mm ( $0.08 \text{ U/cm}^2$ ). This design could be implemented

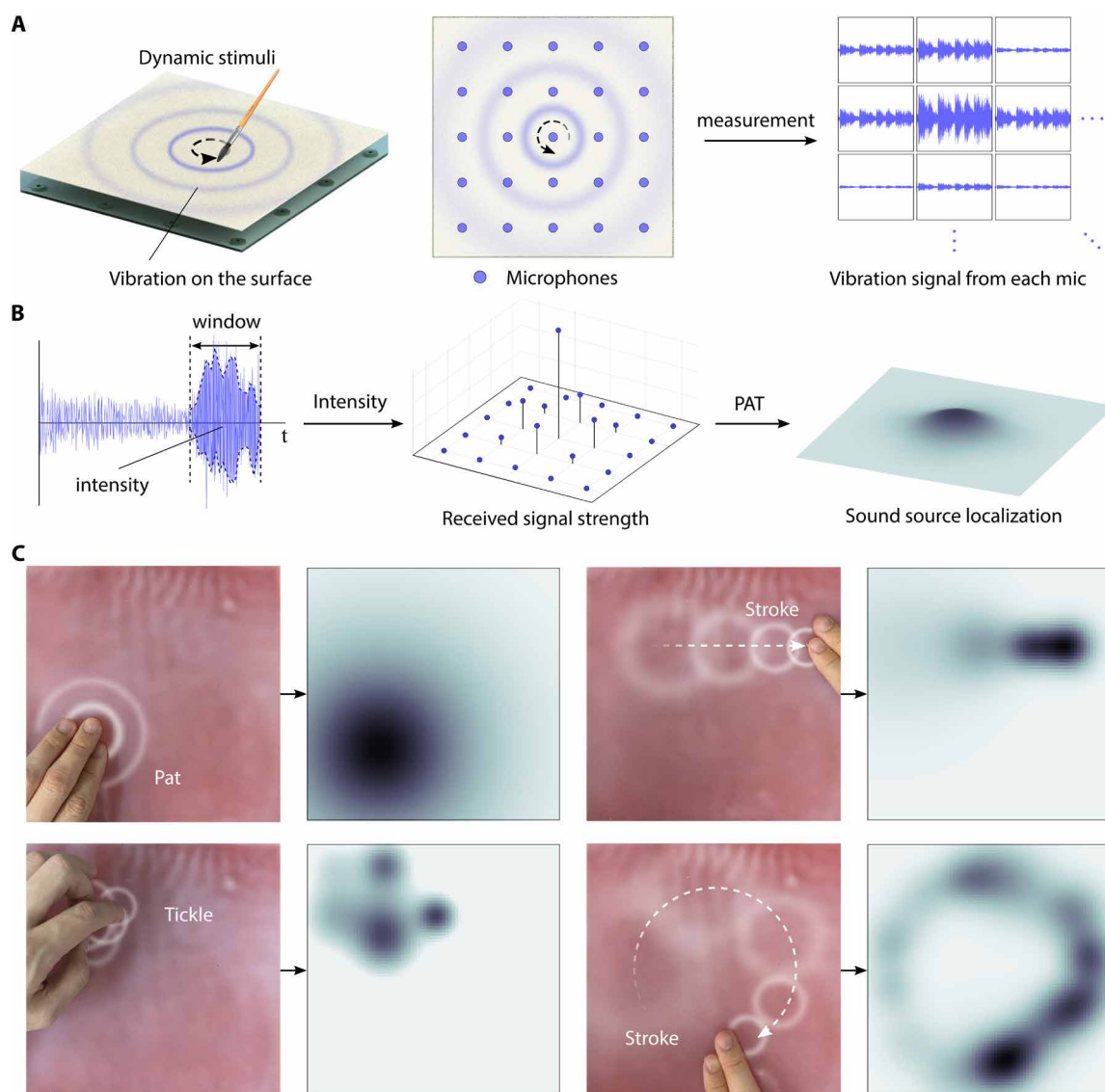
because of the large and overlapping receptive fields of the EIT measurement pattern. A single-point indentation experiment was also conducted to evaluate the contact localization accuracy, and the single-point contacts could be localized with a root mean square (RMS) error of 4.2 mm (figs. S8 and S9). This demonstrates that the EIT allows the robotic skin to achieve tactile superresolution through the interpolation between overlapping receptive fields.

### Dynamic tactile sensing method based on PAT

Human skin also perceives dynamic tactile stimuli through vibration-sensitive mechanoreceptors (Pacini corpuscles). The vibrations are usually generated on skin surfaces by dynamic tactile stimuli, and they are transmitted and recognized by the Pacini corpuscles. Our biomimetic robotic skin senses the dynamic stimuli in a similar way. If dynamic stimuli are applied to the elastomeric skin,

microvibrations are generated and transmitted deep into the sensor through the multilayer structure. The vibrations can be detected by the microphones that are evenly distributed over the base layer (Fig. 3A). Each microphone was also encased in a silicone capsule so that it could sense vibrations generated from a distance of about 5.5 cm (fig. S15). Owing to the large receptive field, the robotic skin could detect stimuli over a large area with a low receptor density ( $0.0625 \text{ U/cm}^2$ ).

Because the energy of vibrations is gradually attenuated as they are propagated, the vibration intensity of each microphone is determined by its distance from the vibration source. Thus, we calculated the position of the dynamic stimulus by applying PAT to the difference in signal strength obtained from each microphone (Fig. 3B and text S2). Each microphone continuously measures the vibration due to touch, and the signal intensity is defined as the power of the



**Fig. 3. Dynamic tactile sensing using PAT.** (A) Measurement of dynamic tactile stimuli using an array of microphones. The microphones were placed as evenly as possible in the remaining space where the electrodes were placed. (B) Localization of dynamic tactile stimuli using PAT and differences in received signal strength. (C) Localization of dynamic stimuli (pat, tickle, and strokes) and their trajectories.

signal within a specific time window. Then, the location of the contact (vibration source) is estimated by minimizing the cost function derived from the decaying model of the vibration.

To demonstrate the localization algorithm, we applied various dynamic tactile stimuli (pat, tickle, and stroke) to the robotic skin, and the PAT algorithm was used to localize the stimuli (Fig. 3C and movie S1). Each image frame was filtered using a weight decaying over time to visualize the trajectory of the stimuli. The results showed that the robotic skin could successfully sense and localize dynamic tactile stimuli using microphones and PAT. To evaluate the localization accuracy, we carried out another experiment whereby we applied a light touch repeatedly to a single point and localized its position using the PAT algorithm. The results showed that the stimulus could be localized with an RMS error of 6.6 mm (fig. S8).

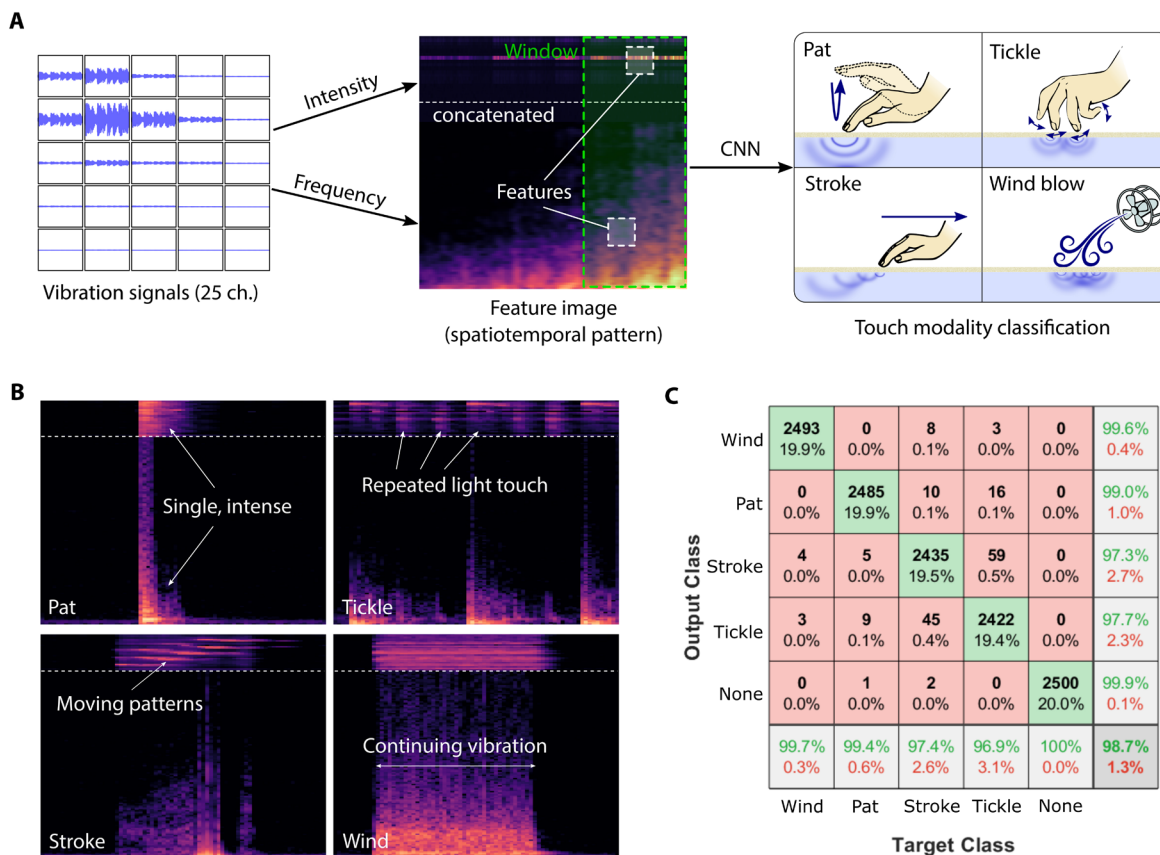
### Touch modality classification using CNN

Humans perceive tactile stimuli through the skin and often interpret these stimuli as social cues or haptic signals with intent. Such a touch modality can be determined according to the intensity, location, and pattern of stimulus. For instance, a tickle consists of repeated light touches, and a stroke produces a continuous and moving vibration pattern. Each stimulus also has its own unique tone. These touch modalities provide additional meaning to simple tactile data such as force or vibration, facilitating tactile communication.

The robotic skin is also able to classify dynamic tactile stimuli (tap and tickle) based on the features of vibration signals because the type of touch determines the spatiotemporal pattern of the vibrations (Fig. 4). First, a history of the vibration intensity from each microphone was obtained. Second, a spectrogram was obtained from the most notable channel to observe the frequency spectrum over time. These 2D arrays were combined to form a feature image that represents the spatiotemporal pattern of the vibrations. Then, the dynamic tactile stimuli could be classified by applying a CNN to the feature image (fig. S7).

To evaluate the classification accuracy, we conducted an experiment to classify touch modality using real measurement data. A dataset from 10 individuals was collected, where each person was asked to continuously apply four dynamic tactile stimuli (pat, tickle, stroke, and wind blow using an air brush). Five hundred feature images for each stimulus were collected from each participant, resulting in 5000 feature images for each stimulus. An equal number of feature images of baseline noise, where no contact is made on the skin, were added to the dataset. The collected dataset was also augmented by a factor of 5 by adding Gaussian noise. Last, the collected dataset was randomly divided into training, validation, and test sets at a ratio of 8:1:1 to avoid overfitting. The trained network classified the test set with an accuracy of 98.7%.

For demonstration, the trained neural network was used to classify the touch modality in real time (movie S2). Dynamic stimuli



**Fig. 4. Classification of dynamic tactile stimuli based on spatiotemporal features of vibration.** (A) A feature image was defined by concatenating the intensity history and spectrogram, which were obtained from the microphones. Subsequently, the spatiotemporal pattern of vibrations was extracted from the feature map using a CNN to classify the stimuli. (B) Examples of the feature images (pat, tickle, stroke, and wind blow). (C) Confusion matrix of the classification results.

were applied to the developed robotic skin to obtain a feature image. Then, the pretrained neural network classified the touch modality based on the feature image in real time. The length of the time window was 0.5 s, and classification was performed every 0.1 s. The result shows that the trained network successfully classified the touch modality; thus, the developed robotic skin is capable of haptic communication with humans by understanding the intention of the touch.

### Repair and restoration of the robotic skin

The developed robotic skin is robust to local damage and repairable. The electrodes and microphones are not directly exposed to external force, so the robotic skin is not totally disabled although the elastomeric skin or hydrogel is damaged (Fig. 5B). The sensor structure can also be easily repaired using adhesives for hydrogels and elastomers. We have demonstrated this reparability. The developed robotic skin was cut with a scalpel, resulting in a loss of electrical connectivity and the inability to detect signals on the skin surface (Fig. 5A). Although the robotic skin was locally disabled due to damage, the tactile sensing capability did not deteriorate at the periphery of the site of damage (Fig. 5B). This result shows that the proposed design is robust to local damage. To repair the robotic skin, we bonded the hydrogel layer using a chitosan topohesive (37, 50). An aqueous solution of chitosan was used to bond hydrogel, and it was placed within the defect for a duration of 30 min (Fig. 5C). The chitosan chains cross-link into a polymer network in topological entanglement with the networks of the cut surfaces. When the cut surfaces adhere sufficiently, the silicone skin is fixed using commercial sealant (Fig. 5D). After repair, the joined part showed a stable

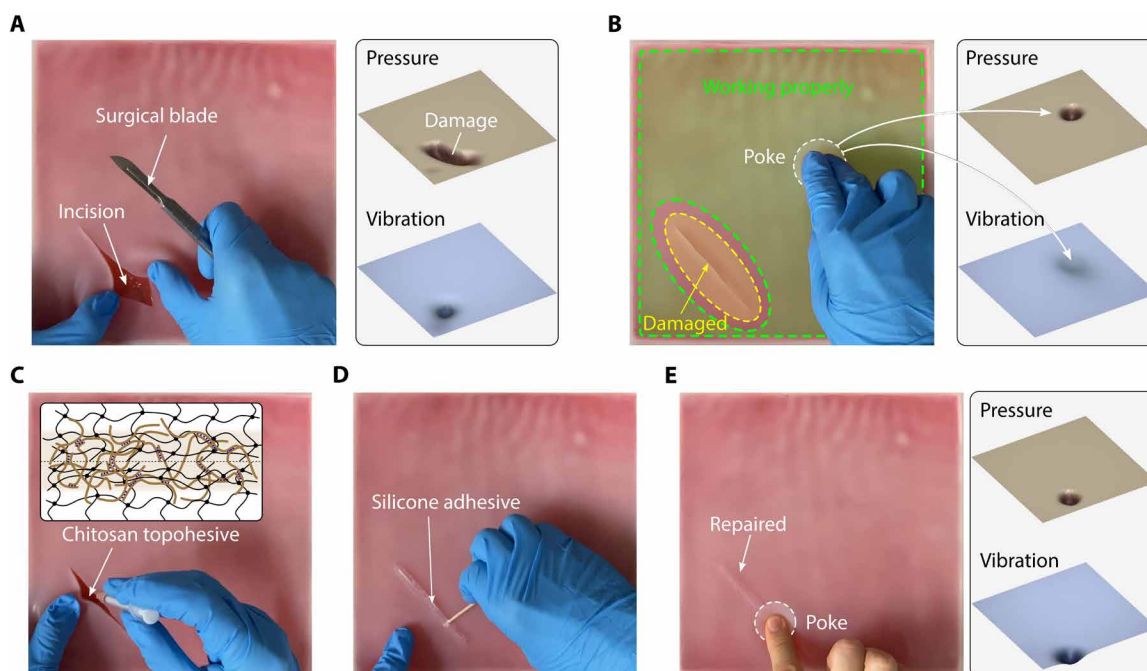
electrical connection again even under deep pressures (Fig. 5E). The repaired robotic skin could localize the force applied to the repaired area, and no artifacts were observed in the reconstructed images (movie S3). Furthermore, the electrical and mechanical connection of the repaired region was stable even under the external force of 20 N (fig. S13). This demonstrates that the structure and function of biomimetic robotic skin can be recovered in an easy and simple procedure.

### Application on a sensorized prosthesis

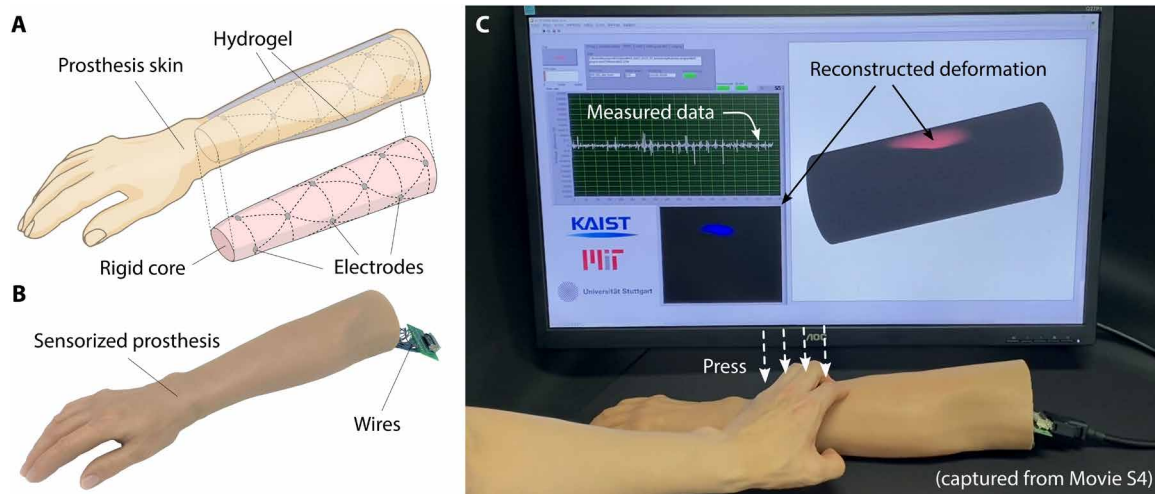
Because we can freely customize the shape of the hydrogel-elastomer hybrid and the arrangement of the sensing elements, the developed biomimetic robotic skin can be easily realized on a large and curved surface. To demonstrate this advantage, we made biomimetic robotic skin for a prosthesis as a proof of concept. The prosthesis was capable of sensing deep pressure through EIT (movie S4). The sensorized prosthesis (cosmetic prosthesis) consisted of an elastomeric skin, ionic hydrogel, and a rigid core with metal electrodes (Fig. 6). Because there is some space inside the rigid core, we expect that the proposed design can be easily integrated into the motorized system. There are currently several challenges in restoring sensory feedback to individuals with impaired sensation due to disease, trauma, or amputation. The proposed robotic skin offers a platform that could be integrated with devices such as prostheses to provide a means for end users to physically interact with their surroundings.

### DISCUSSION

We introduce a biomimetic robotic skin emulating the characteristics of human skin. The design of the multilayered structure with



**Fig. 5. Repairability of the robotic skin.** (A) The robotic skin was cut with a surgical scalpel. The incision resulted in a local loss of electrical connection, which can be observed through the EIT. (B) The robotic skin was locally disabled from tactile sensing due to the damage, but the peripheral regions surrounding the defect remained functional. (C) Chitosan topohesive was applied to the damaged region to bond the hydrogel. Cross-linking of the polymer network was achieved in a pH-responsive technique, thereby bonding the cut surfaces. (D) Elastomeric skin was fixed with a silicone adhesive (room temperature–vulcanizing rubber). (E) The structure and tactile sensing functionality of the robotic skin were restored, including the region with the defect after repair.



**Fig. 6. Application of the biomimetic robotic skin to a cosmetic prosthesis.** (A) Structure of the sensorized prosthesis. The rigid core includes metal electrodes to perform EIT-based tactile sensing. A hydrogel layer was formed between the rigid core and prosthetic skin, and it was used as a pressure-sensing material. (B) An image of the prosthesis incorporating the robotic skin. (C) Demonstration of EIT-based tactile sensing on the prosthetic arm.

distributed sensing elements enables large-area tactile sensing over continuous and curved surfaces, as shown in Fig. 6. Although other methods can achieve this level of tactile sensing performance, the tomographic imaging approach successfully achieves complex curved robotic skin with a relatively simple and practical manufacturing process.

The hydrogel-elastomer hybrid is able to prevent soft tissue injuries from occurring to humans owing to its mechanical properties (32). This robotic skin would provide robots with a tactile sensation, allowing the robot to move to ensure safety. Although the resultant multilayered structure might be relatively heavier than other materials such as foams, the robotic skin can offer close replication of the feeling of human skin (51). This feature is expected to be critical for building empathy and attachment in social robots.

The proposed robotic skin could sense deep pressure and dynamic tactile stimuli through EIT and PAT. These tomographic imaging methods are simultaneously implemented in a biomimetic multilayer structure and complement each other synergistically. This approach also allows the robotic skin to be realized with a low receptor density. The sensing performance shown in Figs. 2 and 3 demonstrates that the developed robotic skin can detect moderate levels of multipoint contacts from light vibratory touch to strong deep pressure. However, the current system cannot distinguish various deformations such as normal indentation and stretch because these deformations had not been considered during the training of the DNN. Nonetheless, such additional deformation regimes can be included by introducing a material with anisotropic resistivity (52) or augmenting the training dataset with simulation results regarding various deformations. It would also be possible to augment the sensing modality by adding artificial intelligence-based sensing methods with different transducing principles such as optical (53) and magnetic (54).

The touch modality could also be classified with an accuracy of 98.7% as shown in Fig. 4, which shows the potential of the developed robotic skin in haptic communication between humans and robots. We also envisage that the number of classifiable modalities can increase if we improve the feature images to include EIT data.

We also demonstrated that the biomimetic robotic skin can be restored after severe damage. This reparability is a practical and necessary feature of robotic skin for pHRI; however, the repair process still has to be conducted manually. In the future, the use of self-healing materials could be explored to more closely mimic human skin (55, 56).

In summary, we have developed a robotic skin by taking inspiration from the native human skin in terms of its architecture and functionality. The proposed design approach can also be further developed by integrating with other transducing methods such as capacitive, magnetic, or optical methods. This study presents an alternative yet practical approach for creating large-area robotic skin, and we envisage that our study would help robots to interact with their environment.

## MATERIALS AND METHODS

### Fabrication of the biomimetic robotic skin

The sensing domain of the robot skin measures 20 cm by 20 cm. The base layer was prepared by cutting an acrylic plate using a laser cutter (Speedy 300, Trotec), and its surface was coated with a silicone elastomer (Dragon Skin 20, Smooth-On). The electrodes were low-head stainless bolts (CBSTSR4-8, Misumi), which were used for EIT. The surface of the electrodes was functionalized using 3-(trimethoxysilyl) propyl methacrylate to form a stable connection between the hydrogels (57). The condenser microphones (CMEJ-4622-25-L082, CUI Inc.) were used to capture the vibration. Thirty-two electrodes and 25 microphones were evenly distributed on the base. The electrodes were firmly fixed on the base layer. The microphones were encapsulated with a silicone elastomer (Dragon Skin 20, Smooth-On) and bonded to the silicone surface of the base layer. The silicone surface and the elastomeric capsules were treated with a 10 weight % (wt %) benzophenone (BP)-ethanol solution, so they could be strongly bonded to the hydrogels through an ultraviolet (UV)-initiated polymerization process.

The biomimetic multilayer structure was made of a silicone elastomer and tough hydrogel (fig. S5). The thicknesses of the elastomeric

skin and the hydrogel were 500  $\mu\text{m}$  and 1 cm, respectively. The elastomeric skin was a large film made with a silicone elastomer (Dragon Skin 20, Smooth-On), and it was treated with a BP-ethanol solution. Other silicone-based parts were also treated with BP solution for the same reason. The hydrogel layer was prepared by mixing a degassed aqueous precursor solution of a polyacrylamide-alginate (PAAm-Alg) tough hydrogel [13.2 wt % acrylamide, 0.8 wt % sodium alginate, 0.02 wt % MBAA (N,N'-methylenebisacrylamide), and 0.2 wt % Irgacure 2959] and calcium sulfate slurry (0.1328 times the weight of sodium alginate). The mixture was mixed quickly and poured onto a BP-treated sensor base. Then, the mixture was covered with BP-treated elastomeric skin to prevent contact with oxygen. We waited 1 hour for the alginate to cure primarily, and then cured the polyacrylamide in the UV cross-linker (CL-3000L, Analytik Jena) for 1 hour. Because all the elements of the robotic skin were chemically treated for bonding with the hydrogel, the developed sensor did not fail or delaminate under external forces.

The sensorized prosthesis is composed of an elastomeric skin (cosmetic prosthesis, Regal) and a rigid core, and the gap between the two parts is filled with tough hydrogel. The inner side of elastomeric skin was treated with a BP-ethanol solution and coated with a PAAm hydrogel (58). The tough hydrogel was prepared by mixing a precursor solution of PAAm-Alg hydrogel [13.2 wt % acrylamide, 0.8 wt % sodium alginate, 0.008 wt % MBAA, 0.0465 wt % APS (ammonium persulfate), and 0.033 wt % TEMED (tetramethylethylenediamine)] and a calcium sulfate slurry (0.1328 times the weight of sodium alginate). The mixture was mixed with a frother and injected using a syringe into the gap between the elastomeric skin and the rigid core. The cosmetic prosthesis was then placed in a water tank to prevent contact with oxygen through the gas-permeable skin. We waited 1 hour for the precursor solution to cure. The hydrogel precursors infiltrated into the hydrogel-coated surface, forming an interpenetrating polymer network during the polymerization process (fig. S14). The materials used were as follows: alginate (Sigma-Aldrich, W201502), acrylamide (Bio-Rad, 1610140), MBAA (Sigma-Aldrich, M7279), TEMED (Sigma-Aldrich, T7024), calcium sulfate (Sigma-Aldrich, C3771), ammonium persulfate (Sigma-Aldrich, A3678), and 2-hydroxy-4'-(2-hydroxyethoxy)-2-methylpropiophenone (Irgacure 2959; Sigma-Aldrich, 410896).

### Preparation of chitosan topohesive

The chitosan topohesive was prepared as described in the paper of Yang *et al.* (50). An acidic buffer solution was prepared by dissolving 0.976 g of 4-morpholineethanesulfonic acid powder (MES hydrate; Sigma-Aldrich, M8250) into 50 ml of deionized water. Sodium hydroxide (Sigma-Aldrich, S5881) was also added to the buffer solution until its pH reached 4.5. Then, chitosan powder (Sigma-Aldrich, 448877) was added to the solution and thoroughly mixed until the chitosan powder was completely dissolved.

### Setup and procedure of indentation experiment

To evaluate the localization performance of the developed robotic skin, we conducted experiments in which tactile stimuli such as pressure or vibration were applied to the sensor surface. The experimental setup is presented in the Supplementary Materials (fig. S9). The plane-shaped robotic skin was placed on a three-axis motorized linear stage (EzRobo-5GX, Iwashita Engineering), and tactile stimuli were applied with an indenter or a vibrator unit depending on the experiment. The first experiment was to apply force to the robotic

skin with an indenter to evaluate the EIT-based contact localization performance. The indenter unit consists of a load cell (651AL, KTOYO) and a hemispherical tip with a diameter of 15 mm. The robotic skin was indented at each node of a  $15 \times 15$  square grid, and the indentation depth was about 7.5 mm (75% of the thickness). During the experiment, the force value, the sensor output, the position of the indenter, and the indentation depth were all recorded. Then, deformation maps were reconstructed from the experimental data, and the localization performance was evaluated by comparing the peak positions with the actually indented positions (fig. S8). The second experiment was to apply vibration to the robotic skin with a vibrator to evaluate the PAT-based vibration localization performance. The vibrator consists of a voice coil motor (LVCM-032-076-02, Moticont), a cross roller guide (VR3-100X14Z, THK), a spring, and a rubber tip. The vibration was applied to a  $13 \times 13$  square grid on the sensor surface, and the frequency of the vibration was 10 Hz. The dynamic tactile stimuli were localized by applying the PAT algorithm to the intensities of the recorded vibration signals, and the results were compared with the actual contact location (fig. S8).

### Setup and procedure for cyclic loading

We conducted a cyclic loading test to investigate the mechanical and piezoresistive properties of the hydrogel-elastomer hybrids. A simple specimen representing the transducing mechanism of the multilayer structure was repeatedly indented using a hemispherical tip with a diameter of 15 mm (fig. S4A). The specimen was prepared with the following dimensions: 40 mm in width, 55 mm in length, and 10 mm in thickness. The electrodes had a radius of 3 mm and were spaced 43 mm from each other. Specimens were compressed up to 8 mm (80% of thickness), and the loading frequency ranged from 0.001 to 4 Hz. During the experiment, the indentation depth, resistance, and force values were continuously recorded, and the signals are processed with a first-order IIR LPF with a 3-kHz cutoff frequency. The result shows that the impedance between two electrodes increases in proportion to the applied force (fig. S4B). The hysteresis of the specimen was quantified by analyzing the loading/unloading curves, and the result shows that the hydrogel-elastomer hybrids exhibit low hysteresis (fig. S4, E and F). The limit of detection was also defined as the force value that changed the sensor output by three times the SD of the measurement noise, and the value was found to be about 0.7 N.

In addition, the cyclic loading test was carried out once more to characterize the change in the material properties of the multilayer structure due to damage and repair. After the first experiment, the specimen was cut with a knife and repaired with the chitosan-based topohesive and silicone adhesive (fig. S13). The repaired specimen was used for cyclic loading test again, and the result shows that the electrical connection and properties under the external force were restored after the repair, supporting both the structural and functional reparability of the biomimetic structure after damage. The material characteristics were slightly changed after damage and repair, but the sensor performance was comparable to that of the intact specimen.

### DNN for EIT

In this study, real-time EIT reconstruction was enabled by setting the model complexity to be moderately light. The training data were obtained by running finite element method simulations instead of directly applying pressure to the sensor (59) because various types of pressure can be applied in the simulation environment. We made

two mesh models: a nondeformed reference mesh model and a mesh model with deformation. These two mesh models calculated the degree of deformation (deformation map  $\delta$ ) and the corresponding measurement voltage ( $v$ ) of the sensor. To accelerate the simulation, the measured voltage was obtained by assigning a conductivity value of zero to the mesh elements corresponding to the indented region instead of regenerating a deformed mesh model every time. Because the simulation data differ from the actual measurement data because of measurement noise and modeling errors, we tried to generalize the model by using a large amount of data and model normalization techniques.

For the machine learning pipeline, we performed latent learning (unsupervised) on the deformation map and EIT measurement vector, and then we obtained a projection between the two latent spaces (fig. S6). The length of the EIT measurement vector was 94, and it was encoded into 84 latent spaces through an autoencoder consisting of a fully connected network (FCN) with an exponential linear unit (ELU) function as an activation function. During autoencoder training, a dropout of 0.03 was added to prevent overfitting, and Gaussian noise was added to the input to make the trained model robust to measurement noise. Because the pattern itself used for measurements was already optimized (60), each measurement data had important information so that the number of neurons in the bottleneck layer could not be greatly reduced compared with the length of the measurement data.

The size of the deformation map was  $48 \times 48$ , and it was encoded into 128 latent spaces through a convolutional autoencoder (CAE). The CAE was also trained with Gaussian noise added to the input stage so that the trained model had a denoising property. The decoder part used an upsampling (nearest) + convolution operation instead of using a transposed convolution. The ELU function was used as an activation function in all layers.

Once the latent learning step was finished, the projection between the two latent spaces was obtained through supervised learning. The latent projections were FCNs with two hidden layers, with 84 inputs and 128 outputs. The number of neurons in the hidden layer was 256 and 256, and the activation function was the ELU function. To prevent overfitting, the encoder and decoder parts were not trained during latent projection training. The trained model could reconstruct the strain map in real time because of its light network structure. In addition, the reconstruction result was robust to measurement noise and showed relatively few artifacts compared with the image obtained through the conventional method (text S1).

### CNN for touch modality classification

Touch modality classification was also performed in real time, similar to DNN-based EIT. The training data were obtained through experiments in which people applied dynamic tactile stimuli directly to the robotic skin. There were 10 people in the experiment, and each person applied four distinct stimuli to obtain 500 feature images for each stimulus. Measurement noise and ambient noise data were also collected for the same number as other stimuli and were labeled “none” to represent the absence of touch. Then, the collected dataset was augmented by adding Gaussian noise. To prevent overfitting, the dataset was randomly divided into a training set, a validation set, and a test set at a ratio of 8:1:1.

The size of each feature image was  $89 \times 41$ , corresponding to a time window with a duration of 0.5 s. To find the spatiotemporal pattern within a feature image, a CNN was used. The size of the first

convolutional layer was  $5 \times 5 \times 32$ , and the image was not padded. The output of the first convolutional layer was input to the batch normalization and rectified linear (ReLU) activation layer. Then, it was downsized through the max-pooling layer. These operations (i.e., conv2D, batch normalization, ReLU, and MaxPool) were repeated once more with a different setting (fig. S7). Last, the output was flattened and progressed through the FCN layer with the softmax activation layer. The network was trained using an adaptive moment estimation (ADAM) optimizer with an initial learning rate of 0.0002, which drops by a factor of 0.1 every five epochs. The size of the mini batch was set to 64, and the cross-entropy loss was calculated every 50 iterations (training with mini batch). The training was set to be aborted if the loss did not decrease more than 20 times. The training was performed using a single GeForce RTX 3070 graphics processing unit. The trained network exhibited a 98.7% classification accuracy on the test set.

### SUPPLEMENTARY MATERIALS

[www.science.org/doi/10.1126/scirobotics.abm7187](http://www.science.org/doi/10.1126/scirobotics.abm7187)

Texts S1 to S4

Figs. S1 to S15

Movies S1 to S4

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## A biomimetic elastomeric robot skin using electrical impedance and acoustic tomography for tactile sensing

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