Geometrically engineered rigid island array for stretchable electronics capable of withstanding various deformation modes

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Integration of rigid components in soft polymer matrix is considered as the most feasible architecture to enable stretchable electronics. However, a method of suppressing cracks at the interface between soft and rigid materials due to excessive and repetitive deformations of various types remains a formidable challenge. Here, we geometrically engineered Ferris wheel–shaped islands (FWIs) capable of effectively suppressing crack propagation at the interface under various deformation modes (stretching, twisting, poking, and crumpling). The optimized FWIs have notable increased strain at failure and fatigue life compared with conventional circle- and square-shaped islands. Stretchable electronics composed of various rigid components (LED and coin cell) were demonstrated using intrinsically stretchable printed electrodes. Furthermore, electronic skin capable of differentiating various tactile stimuli without interference was demonstrated. Our method enables stretchable electronics that can be used under various geometrical forms with notable enhanced durability, enabling stretchable electronics to withstand potentially harsh conditions of everyday usage.

INTRODUCTION

Stretchable electronics enable a wide variety of previously unknown functions by offering various form factors not possible with rigid electronics (1–7). Recently, stretchable display (8–10), battery pack (11–13), sensor array (9, 14, 15), heater (16), and logic circuit (17) have been demonstrated. In stretchable electronics, components (rigid devices, electrodes, and sensors) that are vulnerable to lateral strain have been designed to be protected against mechanical deformation through various geometric engineering (e.g., serpentine, rigid island, and wrinkling). Among them, the strategy of placing non-stretchable devices on the rigid island arrays minimizes the lateral strain applied to the devices because the polymer matrix surrounding islands has a relatively low elastic modulus than the island and is therefore predominantly stretched (4, 10, 11). However, the interfacial cracks between rigid islands and polymer materials due to mechanical mismatch (difference in modulus, stretchability) are likely to occur under excessive or repetitive stretching (18, 19), ultimately leading to crack propagation and device failure. To solve this challenge, several approaches to improving interfacial bonding strength between islands and the polymer matrix have been reported, mainly through chemical treatments (16, 20). However, the usable soft polymer materials are limited, and the organic chemicals are not biocompatible. Furthermore, the fabrication process is not appropriate to produce the devices on the island array because organic chemicals must be coated to specific areas. Therefore, a universal approach to enhance the mechanical stability at the interface is essential to fabricate multifunctional and stretchable electronics capable of withstanding various deformation modes.

RESULTS

Fabrication and characterization of FWI embedded in Ecoflex matrix

Here, we present geometrically engineered rigid islands showing excellent mechanical stability at the interface (Fig. 1A). The interlocking structure in the proposed Ferris wheel–shaped island (FWI) effectively suppresses crack propagation at the interface. The optimized geometrical shapes of FWIs depend on the mechanical properties (e.g., toughness and stretchability) of the polymer materials (e.g., Ecoflex, Dragon Skin, and Ecoflex Gel). The repetitive interlocking structure prolongs the fatigue life against various three-dimensional (3D) deformation modes such as twisting, poking, and crumpling as well as stretching in the 1D direction. Furthermore, we demonstrate several applications taking advantage of the FWI array in Ecoflex and intrinsically stretchable electrode: stretchable electronics operating under various deformations (left image in Fig. 1B) and electronic skin (e-skin) detecting tactile stimuli (right image in Fig. 1B). The proposed approach will greatly enhance the durability of stretchable electronics under practical usage, thus strengthening their commercial viability.
were prepared using polylactic acid (PLA) (modulus: 4 GPa) (31) and Ecoflex (modulus: 50 kPa) (32) as islands and polymer, respectively (fig. S1). Under stretching, failure at the interface between the CI and the Ecoflex was observed at 75% (Fig. 1C). On the other hand, when the FWI was used, there was no substantial interfacial failure even when it was stretched at 175%. This indicates that the FWI is effective in suppressing crack propagation, thus increasing stretchability. Through inflection point (i.e., sharp drop in the stress) in the stress-strain curve (s-s curve), the strain at interfacial failure was obtained (Fig. 1E). The inflection point occurs because of the Ecoflex near the rigid islands being ruptured, which dissipates large amounts of interfacial fracture energy. The FWI, in particular, had excellent stretchability compared with various shapes generated randomly (fig. S2). Furthermore, FWI had omnidirectional stretchability, while square- and hexagon-shaped islands were easily ruptured when stretched at specific angles (Fig. 1F).

To observe the progress of the crack propagation at the interface under stretching, we used digital image correlation (DIC) analysis to obtain the strain distribution of Ecoflex near and on the islands (Fig. 1D and fig. S3). At the interface of the CI, cracks appeared at a strain of 70%, and at 75% strain, the crack propagated substantially to cause interfacial failure. On the other hand, at the interface of the FWI, cracks did not occur until a strain of 180%. However, even at this strain, the anchored Ecoflex region suppresses crack propagation. It was confirmed that this crack propagation suppression effect exists even in small-scale FWI applicable to soft ultrathin electronics (fig. S4). We have also confirmed mechanical interlocking effect from the strain measurement along the polymer-island interface using DIC analysis (fig. S5). It was also confirmed that the FWI in Ecoflex was effective in suppressing crack propagation despite the presence of a preexisting crack that normally induces crack propagation (fig. S6).
The process of deriving and optimizing the design of FWI

The process of deriving the FWI is as follows (Fig. 2A): (i) Compared with square- and hexagon-shaped islands, CI has a 360° omnidirectional stretchability. (ii) Cracks at the interface of the CI easily propagate, while the periodic teeth in the windmill-shaped island (WMI) deflect the progress of cracks, thereby delaying interfacial failure. (iii) The FWI, where the mechanical interlocking structure is implemented, stops the progression of the crack by creating anchored Ecoflex regions. This interlocking effect was maximized when the ratio of the inner diameter to the outer diameter reached 0.42 (fig. S7). In addition, when several shapes of mechanical interlocking structures were formed, the strain at failure of the FWI was higher than that of WMI (fig. S8). To optimize the shape of the interlocking structure, we fabricated 16 different FWIs using the 3D printer for the design of experiments method (table S3) (33). We used analysis of variance (ANOVA) to evaluate percent contribution of various design parameters [the number of teeth (n), p/i ratio, a/b ratio, and c/i ratio] to the strain at failure (Fig. 2B). As a result, the contribution of the number of teeth, p/i ratio, a/b ratio, and c/i ratio to the strain at failure were 46.43, 24.27, 19.02, and 10.28%, respectively. Therefore, it was confirmed that the number of teeth had the greatest contribution among the design parameters. To study the effect of the number of teeth of WMIs and FWIs on suppressing the progression of cracks, the strain at failure was obtained from the s-s curve (Fig. 2C and fig. S9). It was observed that the process of crack propagation was different for each shape (fig. S10).

To understand the effect of island designs on the stretchability of the devices, a finite element (FE) simulation was performed. The crack propagation between the rigid island and the polymer matrix was simulated as the matrix was stretched along the uniaxial direction (Fig. 2D). The detailed procedure for the simulation is explained in Materials and Methods. To quantitatively compare the resistance to crack propagation according to the island shape, the failure criterion was set to be satisfied when crack opening displacement (COD) reached 2.5 mm (Fig. 2E). First, the CI had overall strain at fracture of 8.9%, and cracks propagated monotonically along the edge of the
Case 2) Peeling dominant

Figure 3: Compatibility of FWIs with various polymer materials. (A) Schematic illustration of two types of complete interfacial failure in FWI in polymer substrate. (B to D) Strain at failure according to the p/i ratio change of (B) Dragon Skin, (C) Ecoflex, and (D) Ecoflex Gel. (E) Schematic illustration of FWIs with different p/i ratios. Each box represents the optimized FWI of each polymer. (F) Experimentally obtained strain at failure for CI (white bars) and FWI (blue bars) in three different polymer matrices (Dragon Skin, Ecoflex, and Ecoflex Gel). Scale bars, 5 mm (B to D). Photo credit: J. C. Yang, KAIST.

Compatibility of FWIs with various polymer materials

When the substrate with FWIs is stretched to the maximum, interfacial failure occurs in two modes, written as case 1 (fracture dominant) and case 2 (peeling dominant) in Fig. 3A. For case 1, the narrow region between the teeth (i.e., the neck region) fractured while the anchored region remained intact, whereas for case 2, the anchored
region completely peels off of the island. Which failure mode the FWI undergoes depended on the type of polymer matrix material (Ecoflex, Dragon Skin, and Ecoflex Gel) and the p/i ratio (fig. S15). Figure 3B shows the strain at failure of the FWI with different p/i ratios in Dragon Skin. When the p/i ratio was below 0.25, the thin neck was vulnerable to fracture; hence, case 1 failure occurred (left inset image in Fig. 3B). In addition, as the p/i ratio increases, the strain at failure increases as the neck becomes thicker. On the other hand, when the p/i ratio was higher than 0.25, the neck region did not fracture; rather, the anchored region peeled off of the island (case 2) (right inset image in Fig. 3B). As the p/i ratio increases furthermore, the strain at failure decreases as the anchored region becomes easier to peel off. Therefore, at the transitional point (p/i = 0.25), strain at failure was the maximum. Figure 3C shows the strain at failure of the FWI with different p/i ratios in Ecoflex. In the case of Ecoflex, it showed similar behavior to Dragon Skin with a transitioning point at p/i = 0.33. When Ecoflex gel, which has a relatively low toughness, was used, case 1 failure occurred at all p/i ratios (Fig. 3D). Therefore, maximum strain at failure occurs when p/i is 0.83, where the neck is the thickest. Figure 3E shows 2D drawings of FWIs with different p/i ratios. It was found that the lower the toughness of the polymer materials (fig. S16), the higher the optimum p/i ratio was. When the FWIs with optimized p/i ratios (blue bars) were used, strain at failure was improved for all three polymer types compared with that of CIs (white bars) (Fig. 3F). For this study, Ecoflex was chosen as a substrate for stretchable electronic demonstrations. Among the three materials tested (Dragon Skin, Ecoflex, and Ecoflex Gel), Ecoflex has moderate values of both modulus and stretchability, making it suitable for stretchable electronics.

**Mechanical reliability of the substrate with FWIs**

The effective suppression of crack propagation of FWIs not only enhances stretchability but also prolongs fatigue life. Fatigue tests were conducted on CI at 70% strain and on FWI at 120% strain, respectively (Fig. 4, A and B). In the case of CI in Ecoflex, the s-s loops shifted downward along the y axis within 100 to 140 cycles, which confirms rapid interface failure. On the other hand, the s-s loops of FWI in Ecoflex overlapped for 1000 cycles even at a higher strain, and no interfacial failure was observed. Figure 4C shows the relative change in the modulus [i.e., slope of the s-s curve (E)] divided by the original slope (E0)] according to the number of cycles. At around 140 cycles, the E/E0 of CI drops to 0.7 because of interfacial failure, whereas for FWI, no such failure occurs. In both CI and FWI, the viscoelastic property of the Ecoflex led to mechanical hysteresis (gradual shifting along the y axis) of the s-s loops over cycles (34).

The FWI with strong horizontal crack propagation resistance also contributed to the mechanical stability under various 3D deformations. Fatigue tests were performed on CI and FWI under twisting, poking, and crumpling. To verify the mechanical stability of FWIs under twisting, a cyclic tensile strain of 60% was applied to the CI and FWI in Ecoflex twisted at specific angles (180° and 360°) (Fig. 4D and fig. S17). Figure 4E shows the change in the modulus according to the cycles. Under cyclic stretching at 180° for CI in Ecoflex, the E/E0 decreased to 0.9 within 20 to 25 cycles, signifying interfacial failure (fig. S18A). Figure S18B shows the failure at the interface immediately upon twisting at 360° for CI in Ecoflex even without applying strain. On the other hand, the E/E0 of FWI in Ecoflex twisted at 180° and 360° remains relatively constant, indicating a highly stable structure under twisting (fig. S18, C and D). The initial decrease in E/E0 is due to the viscoelastic property of the Ecoflex.

To investigate the resistance to crack propagation when stress is applied along the thickness of the substrate (i.e., applying shear stress by poking), cyclic pressure of 10 kPa (compressive force: 3 N, depth: 1.6 cm) was applied to the CI and FWI in Ecoflex (suspended in air) at 60% lateral strain (Fig. 4F and fig. S19). Figure 4G shows the change in the pressure (P/P0) according to the number of cycles. For CI in Ecoflex, interfacial crack easily propagated, resulting in an immediate decrease in pressure. The inset image in Fig. 4G shows the fractured CI in Ecoflex at the 11th cycle. The FWI in Ecoflex exhibited a slight decrease in P/P0 up to 50 cycles, which is due to the viscoelastic property of the Ecoflex. Thereafter, the FWI in Ecoflex was stable without interfacial failure up to 1000 cycles. This result shows that FWI also impedes failure along the thickness of the substrate.

To test failure under crumpling mode, we first fabricated CI and FWI (thickness: 1 mm) array (3 × 3) embedded in Ecoflex. The island arrays were placed inside a cylinder and repeatedly crumpled vertically 100 times with pressure of 35 kPa (force: 70 N) (Fig. 4H). Top of Fig. 4H shows that in the case of CI, cracks rapidly expanded through the interface between islands and the Ecoflex. On the other hand, no visible crack propagation occurred in the case of FWI (bottom of Fig. 4H). In summary, the fatigue tests for stretching, twisting, poking, and crumpling suggest that the FWI suppresses crack propagation at the interface even when repetitive external force of various types is applied. These results signifiy that, through our geometrical design, stretchable electronics can potentially gain degrees of freedom to different deformations, thus propelling stretchable electronics toward many practical applications operated under harsh conditions.

**Stretchable electronics with rigid components**

Previously, rigid islands and various serpentine electrodes have been used to integrate conventional rigid components into stretchable electronics (10, 11, 23). Serpentine electrodes are vulnerable to repetitive deformation because of weak interface with the polymer matrix and due to its intrinsic brittleness. Therefore, for the devices to operate stably under various repeated deformations, Ag flake/Ecoflex composite (35), which is an intrinsically stretchable electrode, was used (Fig. 5A and Materials and Methods). The composite solution containing 82 weight % of Ag flakes with respect to Ecoflex was screen printed on Ecoflex substrate with and without islands through a metal mask. It was confirmed that the electrode on the Ecoflex substrate without island has high initial electrical conductivity of 400 S/cm and high stretchability of 295% (Fig. 5B). Compared with the CI in Ecoflex, the electrode coated on the FWI in Ecoflex maintained low resistance at a higher strain (27 ohms at 220% strain) due to its high interfacial stability. In addition, the stretchable electrode on the FWI in Ecoflex maintained low resistance even at 1000 cycles (fig. S20). To fabricate stretchable electronics, FWIs were prepared in the form of an array; here, the spacing between the islands determined the maximum stretchability of the array (fig. S21). To produce a stretchable light-emitting diode (LED) array, an FWI array of 3 × 3 in Ecoflex was prepared with a center-to-center distance of 25 mm between the islands (Fig. 5C and Materials and Methods). Then, stretchable electrodes were printed, followed by the placement of surface mount device (SMD) LED chips on each FWI and fixation with PDMS prepolymer.
were hexagonally arranged (27). A battery pack, two arrays were prepared in which seven FWIs and bending (Fig. 5D and movie S1). Next, to manufacture a stretchable battery pack, the exposed electrodes were encapsulated with Ecoflex. The manufactured stretchable LED array worked well under all deformation modes, including stretching, twisting, crumpling, and bending (Fig. 5F and movie S2). Such freeform electronics is expected to increase user convenience and durability under practical usage.

### E-skin with pressure and strain sensors

For practical usability of e-skin toward various applications such as virtual reality/augmented reality, human-machine interface, health monitoring, and robotics (6, 36–38), it is of critical importance to differentiate physical stimuli without signal interference while ensuring high durability under repeated and excessive mechanical deformations. Using FWI array in Ecoflex, e-skin that can differentiate physical signals under various deformation modes was demonstrated (Fig. 6A). Four polypyrrole-coated micropyramidal PDMS-based piezoresistive pressure sensors (39, 40) were placed on the FWIs, and two porous carbon nanotube (CNT)/Ecoflex composite–based
piezoresistive strain sensors (41) were coated on the Ecoflex (see Materials and Methods and figs. S22 and S23). Scanning electron microscopy (SEM) images confirm microstructures of the pressure and strain sensors (fig. S24). The piezoresistive pressure sensors detect pressure levels through the change in contacting area between two lateral electrodes and the polypyrrole-coated micropyramidal PDMS (fig. S25A). The pressure sensors not placed on FWIs were subject to electrical interference under lateral strain (fig. S25B). Pressure sensors placed on CIs have reduced signal interference because of lateral strain; however, they lack practical feasibility because of the disconnection of the electrodes under high strain (fig. 6B). The pressure sensors on FWIs, on the contrary, measured the same pressure without the interference even under strain up to 150%. Furthermore, the two piezoresistive strain sensors coated on
Fig. 6. E-skin distinguishing pressure and lateral strain. (A) Schematic illustration of e-skin consisting of polypyrrole-coated micropyramidal PDMS-based pressure sensors and porous CNT/Ecoflex-based strain sensors. The area within the red dotted line is isolated from lateral strain. (B) Sensing characteristics of pressure sensors placed on the region of CI and FWI in Ecoflex under stretching. The pressure sensor on the CI does not work because of the electrically disconnected electrode at 70% strain. (C) A radial artery pulse signal detected by the pressure sensor. (D) A signal due to bending of the knee detected by the strain sensor. (E) Real-time monitoring of pressure and lateral strain in various deformations: (i) pressure on the substrate and (ii) stretching the substrate along the x-axis and pressure on the biaxial-stretched substrate. Photo credit: J. C. Yang, KAIST.
the Ecoflex of substrate accurately detected lateral strain in the $x$ axis and $y$ axis directions. In particular, our strain sensor was designed to be insensitive to pressure (fig. S26) (41). For demonstration toward health care monitoring, our e-skin was attached to a human forearm to detect human pulse from a pressure sensor (Fig. 6C). The measured pulse rate was 69 beats min$^{-1}$. The p-, t-, and d-waves in the waveform of radial artery pulse were matched with the subject’s age of 29 (40, 42). The average values of digital volume pulse time ($\Delta T_{DVP} = t_2 - t_1$), radial augmentation index ($AI_r = P_2/P_1$), and diastolic augmentation index ($DAI_r = P_3/P_1$) were 0.188, 0.840, and 0.530, respectively. These values can be used for health care monitoring. In addition, information on daily movements can be collected and used for health care monitoring through the strain sensor attached to the knee (Fig. 6D). Complex tactile stimuli with simultaneous input of strain and pressure were effectively decoupled in real time when our e-skin was attached to the skin and when held with hands (Fig. 6E). Furthermore, our e-skin produced the same sensor signal even at 1000 cycles (fig. S27).

**DISCUSSION**

For practical use of stretchable electronics in the future, it is of high importance to ensure high durability under potentially harsh conditions that the devices can be exposed to under everyday usage. In this sense, simple lateral strain testing is insufficient to qualify stretchable electronics toward practical applications. To bridge this gap, we developed FWIs with strong mechanical stability at the interface with soft polymer. Because of suppression of interfacial crack propagation by the interlocking structure, the FWI improved strain at failure under stretching and prolonged fatigue life under various deformation modes (stretching, twisting, poking, and crumpling). Various design parameters of FWI have a great influence on the mechanical stability of the substrate and depend on the mechanical properties of polymer materials. For practical demonstrations of stretchable electronics, we printed intrinsically stretchable electrodes and placed rigid components (LED and coin cell) on the FWI arrays. Furthermore, we fabricated e-skin capable of differentiating various physical stimuli. Our technique can be generally applied to a wide variety of stretchable electronics to impart high durability under various deformation modes, thus bringing stretchable electronics closer to commercialization in the near future.

**MATERIALS AND METHODS**

**Fabrication of rigid island with various shapes embedded in polymer matrix**

PLA islands with various shapes (table S2) were manufactured with a 3D printer (Ultimaker 2+, USA). The type of printer is fused deposition modeling technology. The diameter of the island was 20 mm. The height of the island used in Figs. 1 to 4, and 5 and 6 were 5 and 1 mm, respectively. Ecoflex 00-20 (Smooth-On), Dragon Skin 10 NV (Smooth-On), and Ecoflex Gel (Smooth-On) were used for the elastic polymer matrix. The part A and part B of the Ecoflex series (Ecoflex, Dragon Skin, and Ecoflex Gel) in a 1:1 weight ratio were mixed with a planetary mixer (Thinky AR-100) to perform a mixing time of 2 min and a deformation time of 30 s. The PLA islands were placed on the mold, and the prepolymer solution was poured equal to the height of the island. The curing conditions for Ecoflex Gel were 3 hours at room temperature. The curing conditions for Ecoflex and Dragon Skin were 1 hour at 80°C. In all cases except for Fig. 3, Ecoflex was used as the polymer matrix. After the curing process, the samples were prepared by cutting polymer matrices into 50 mm × 70 mm × 5 mm.

**Fabrication of intrinsically stretchable electrode**

The previously reported Ag flake/Ecoflex composite–based electrode was used (35). First, MIBK (4-methyl-2-pentanone) (Sigma-Aldrich), Ecoflex prepolymer solution, and Ag flakes (Daejoo Electronic Materials) were mixed in a 3:3:14 ratio with a planetary mixer to perform a mixing time of 2 min and a deformation time of 30 s. Afterward, the Ag flake/Ecoflex composite solution was screen printed on the CIs and FWIs in Ecoflex substrate to a thickness of 200 μm through a metal mask. The heating condition was 1 hour in 80°C and 2 hours 30 min in 110°C. The MIBK solvent was evaporated at 80°C, and conductivity was achieved through thermal sintering of the composite at 110°C.

**Fabrication of stretchable LED array and stretchable battery pack**

To fabricate a stretchable LED array, an FWI (thickness: 1 mm) array of 3 × 3 was placed on the mold in square packing. The Ecoflex prepolymer solution was poured equal to the height of the island. The center-to-center distance between the islands was 25 mm. Ag flake/Ecoflex composite was screen printed on the FWIs in Ecoflex substrate to a thickness of 200 μm through a metal mask. Afterward, the SMD LED chips (5 V; GrinMax) were attached to the island. Then, SMD LED chips were placed on each FWI and fixed with PDMS. The exposed electrodes were encapsulated with Ecoflex. Next, to manufacture a stretchable battery pack, two arrays were prepared in which seven FWIs (thickness: 1 mm) were hexagonally arranged with a center-to-center distance of 30 mm between the islands. The process of manufacturing arrays with electrodes was the same as that of the stretchable LED array. Then, lithium coin cells (3 V; Panasonic) were sandwiched between these two arrays with PDMS fixation and Ecoflex encapsulation. To operate the stretchable LED array and stretchable battery pack, Ag-coated mesh (Shieldex) was connected to Ag flake/Ecoflex and encapsulated with Ecoflex. To turn on the LEDs, the voltage was applied to the stretchable LED array through a source meter (Keithley 2400, Tektronix Inc.). The stretchable battery pack was connected to the diode.
lower the viscosity. The Ecoflex prepolymer solution was used instead of the PDMS prepolymer solution, and the fabrication process was the same as in previously reported work. The CNT/Ecoflex solution was screen printed on the Ecoflex region of the substrate. The width and length of the CNT/Ecoflex layer are 5 and 40 mm, respectively. To operate the e-skin, Ag-coated meshes (Shieldex) were connected to stretchable electrodes and encapsulated with Ecoflex.

**DIC analysis**

Strain distribution on the surface of the stretchable substrate specimens was calculated and analyzed using a commercial DIC algorithm program (ARAMIS, Gesellschaft für Optische Messtechnik mbH) during a tensile test with 0.005% error for strain measurement. Analyzed images were captured at 3 Hz by two charge-coupled device (CCD) cameras (6 million pixels), which were calibrated to measure the proper area (170 × 110 mm). CCD cameras and commercial software were calibrated to measure a large enough area to capture the images of 100%-stretched specimens (fig. S28). We applied the interpolation method at the boundary of the island, which calculates strain as the average of the island and the matrix region. Both black and white speckle patterns were randomly generated on both the matrix and the island simultaneously by commercial lackspray (Dupli-Color, Germany).

**FE simulation**

The interfacial crack propagation process for various shapes was simulated using a commercial FE method tool (Abaqus version 6.14-3). The island, matrix, and grips at both ends were modeled as a deformable 2D shell. The element type of the components was CPS4R (four-node bilinear, reduced integration with hourglass control) (fig. S29). The island was bonded to the matrix based on the VCCT model with uniformly distributed microcracks at the outermost surface, under the assumption that the interfacial fracture energy is much smaller than the cohesive fracture energy of the island. The island was modeled to be a rigid body with various shapes (circle, windmill, and Ferris wheel), with an outer diameter of 10 mm. The matrix was drawn to dimensions of 50 mm wide and 100 mm long.

**Tensile test and fatigue test**

Tensile test and fatigue test were performed on CIs and FWIs using a force gauge (maximum force: 100 N, Mark-10) and a stand with a motor (Mark-10). In all the tests, the strain speed of the motor was 200 mm/min. In the fatigue test under twisting, repetitive stretching was applied to the twisted substrate. In the fatigue test under poking, repetitive pressure was applied to the stretched substrate. To test the crumbling mode, an FWI (thickness: 1 mm) was placed inside of a cylinder and repeatedly crumpled vertically 100 times with pressure of 35 kPa (force: 70 N).

**Measurement of electrical properties**

The resistance of the stretchable electrode, pressure sensor, and strain sensor was measured using an inductance capacitance and resistance (LCR) meter (4284A, HP) at 1-V voltage and 1-kHz frequency. In Fig. 6E, we used Arduino to obtain pressure and lateral strain signals simultaneously in real time (fig. S23C). All experiments on human skin were not subject to local ethics committee approval because noninvasive measurement of skin was conducted.

**SUPPLEMENTARY MATERIALS**

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