

# Shape memory polymer adhesives for on-demand, low-force detachment in skin-interfaced devices

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Skin-interfaced biomedical devices require adhesives that provide strong attachment during use while enabling gentle removal with minimized subsurface skin deformation. Conventional medical adhesives lack mechanisms for on-demand adhesion modulation, often causing skin irritation and damage during detachment, particularly in vulnerable populations. Here, we present a thermally triggered shape memory polymer (SMP) adhesive that achieves reversible, high-contrast adhesion switching through programmable pyramidal structure recovery. The adhesive incorporates an array of pyramidal structures that remain flattened in a dormant state to ensure robust skin adhesion, but rapidly recover upon mild heating above the glass transition temperature, significantly reducing effective contact area and enabling low-force detachment. Adhesion switchability performances are supported by quantitative mechanical measurements, including reductions in peel force and adhesion energy after activation, as well as three-dimensional digital image correlation (3D-DIC) analyses demonstrating minimal subsurface skin deformation during detachment. Mechanical testing demonstrates up to ~99% reduction in adhesion energy upon activation, while maintaining stable load-bearing performance during use. 3D-DIC shows that the actuated SMP suppresses stress concentrations and minimizes subsurface skin deformation during detachment, unlike the dormant SMP. A kirigami structural design further enhances conformability on both singly and doubly curved anatomical surfaces while improving water vapor permeability. Finite element analysis and 3D-DIC measurements reveal substantial reductions in effective stiffness and enhanced bending accommodation enabled by the kirigami geometry. Integration with wireless mechano-acoustic sensors confirms reliable physiological signal acquisition in the dormant state and controlled detachment upon activation. This work establishes a thermally switchable SMP adhesive platform for low-force removal of skin-interfaced devices.

Continuous monitoring of physiological signals is increasingly central to modern medical care, guiding diagnosis, treatment adjustment, and patient management across diverse clinical settings<sup>1</sup>. Many of these systems rely on skin-mounted sensors that must remain securely

attached for extended periods while still allowing removal for repositioning or replacement<sup>2–7</sup>. Conventional medical adhesives provide the required level of adhesion and signal stability but introduce substantial drawbacks, particularly for individuals with delicate or compromised

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skin. Premature infants, young children, elderly patients, and those in intensive care are especially susceptible to irritation, epidermal stripping, and other forms of skin injury caused by strong adhesive bonds during device removal<sup>18–10</sup>.

Switchable adhesives are interfaces whose adhesion can be reversibly tuned between strong and weak states through external stimuli, including mechanical loading, temperature, and material stiffness changes. In biomedical applications, switchable adhesion is particularly important because medical tapes, wearable sensors, and wound dressings must adhere securely during use but release gently to avoid skin damage. Recent review articles highlight a broad landscape of medical adhesives that achieve switchable adhesion through dynamic covalent chemistry, supramolecular interactions, hydration control, or temperature dependent network rearrangement<sup>11,12</sup>. Dynamic covalent and supramolecular hydrogels can form strong wet adhesion yet dissolve or weaken when exposed to specific molecules or pH changes<sup>11,13–15</sup>. Trigger removable bioadhesive tapes achieve tough bonding to tissues but detach benignly when a biocompatible solution disrupts interfacial interactions<sup>16</sup>. Electroadhesive patches generate temporary adhesion through low-voltage fields that deactivate upon power removal<sup>17</sup>. Temperature responsive adhesives for skin-mounted electronics stiffen to create stable contact during monitoring and soften for painless removal under mild heating or cooling<sup>18–20</sup>. Hydration-responsive systems, such as porous mineral-based adhesives, also enable strong adhesion in dry environments and rapid release when wetted<sup>21</sup>. Notably, thermally switchable silicone-based adhesives incorporating phase-change components have been demonstrated to enable on-demand adhesion reduction for skin-interfaced wireless devices through mild heating<sup>22</sup>. More recently, thermoresponsive conductive hydrogels have achieved reversible skin adhesion through lower critical solution temperature-mediated phase transitions, while temperature-mediated phase separation has been employed in cellulose nanofibril-reinforced hydrogels to dynamically regulate hydrogen-bond interactions and enable strong yet reversible skin adhesion<sup>23,24</sup>. Unlike these chemistry-driven approaches, the present work utilizes thermally activated SMP pyramidal structures to mechanically reduce the effective contact area and enable detachment through a geometry-driven mechanism. Collectively, these studies demonstrate the promise of switchable adhesives for biomedical use, although systems that achieve large adhesion contrast between the attached and detached states while enabling near-force-free detachment from skin remain limited.

Microstructured polymer surfaces offer an attractive route to achieving high-contrast adhesion switching due to their ability to reversibly modulate contact area through shape deformation. Early examples include gecko-inspired elastomeric microstructured elastomers that tune adhesion by altering shear direction or preload, providing controllable attachment on smooth surfaces<sup>25–27</sup>. Elastomer stamps used in transfer printing further demonstrated switchable adhesion at the microscale by exploiting viscoelastic rate effects to control interfacial fracture energy<sup>28,29</sup>. More recently, shape memory polymer (SMP) based dry adhesives have achieved large adhesion switching ratios by altering stiffness and surface topography through thermal programming, yielding adhesion modulation exceeding three orders of magnitude<sup>30–32</sup>. Recently, thermally responsive tessellated SMP adhesives have demonstrated high-contrast adhesion switching by coupling conformal surface adaptation with crystallization-induced stiffening and shape-memory-assisted detachment<sup>33</sup>. Recent studies further revealed that rubber-to-glass transitions and shape-locking effects in SMPs can dramatically enhance adhesion strength and surface adaptability through thermally locked conformal contact<sup>34,35</sup>. Recent reviews have also highlighted SMPs as a potential platform for next-generation smart dry adhesives due to their tunable stiffness, shape-locking capability, and reversible shape-memory behavior<sup>36</sup>. Such thermally reconfigurable SMP systems rely on reversible phase

transition and crystallization-driven shape-evolution mechanisms that enable programmable and repeatable surface deformation<sup>37</sup>. Such polymer-based adhesives provide highly reversible and residue-free adhesion across both macro- and microscale applications.

Here, we introduce a thermally switchable biomedical skin adhesive based on an SMP that achieves robust attachment during use and gentle, low-trauma detachment through a simple, geometry-driven mechanism. The adhesive incorporates an array of pre-programmed pyramidal structures that remain flattened and strongly adherent during normal use but reappear rapidly upon heating above the glass transition temperature of the SMP. This topographical transition significantly reduces the effective contact area with the skin, enabling gentle, low-force detachment that minimizes irritation. Because activation requires only mild heating and the SMP remains stable at typical skin temperatures, the system avoids unintended release during wear while allowing on-demand detachment when desired.

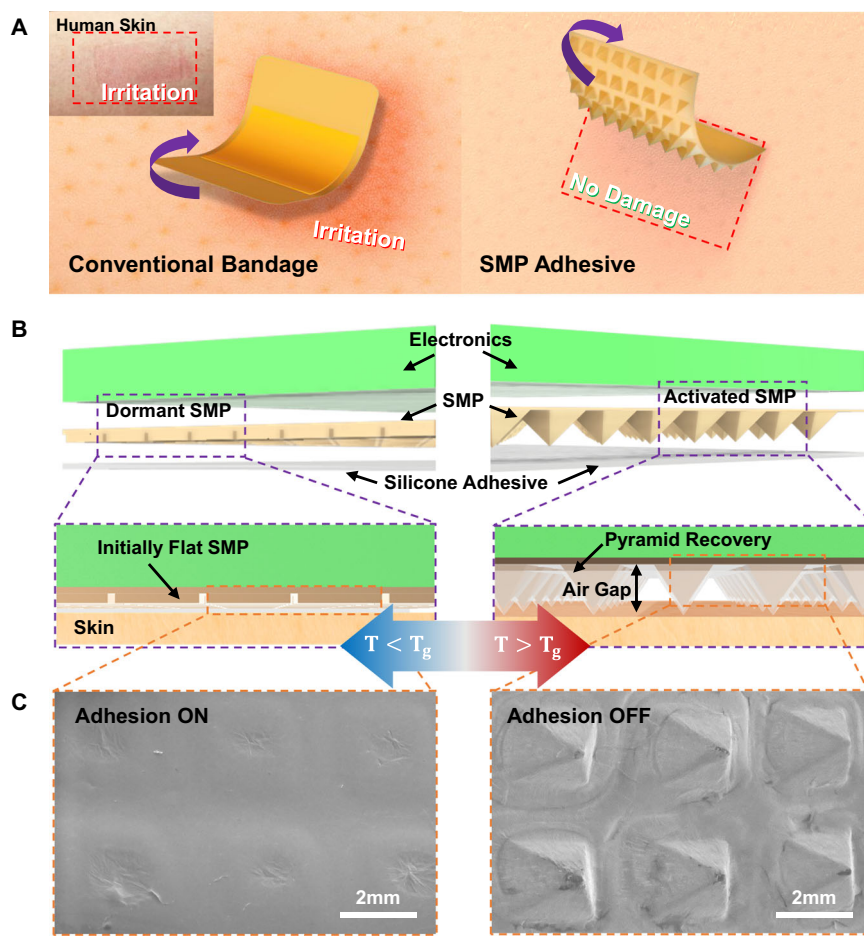
We systematically investigate the mechanics of pyramidal structure recovery, quantify adhesion switching behavior, and optimize geometric parameters to maximize adhesion reduction. Skin deformation during detachment is visualized using three-dimensional digital image correlation (3D-DIC). To enable conformal attachment on highly curved and sweat-prone anatomical sites, we further introduce a kirigami structural design that enhances mechanical compliance and moisture permeability. Finally, we demonstrate compatibility with wireless mechano-acoustic sensing devices, validating that the adhesive provides stable signal transmission in the dormant state and controlled detachment with signal suppression upon activation.

## Results

### Thermally controlled adhesion switching enabled by SMP pyramidal structure recovery

As shown in Fig. 1A, conventional medical bandages and patch-type adhesives (left) lack any mechanism to reduce adhesion during removal, often causing significant irritation and tissue damage. Because their adhesion remains strong both during use and throughout peeling, the detachment process concentrates stress on the skin and readily induces reactions such as erythema. To address this issue, we propose a low-trauma adhesive based on an SMP, which actively modulates its surface topography in response to thermal stimuli. When heated above its glass transition temperature ( $T_g$ ), the SMP adhesive recovers its pre-programmed pyramidal structure, effectively reducing the contact area with the skin and reduced peel force and suppressed interfacial stress concentration in detachment. This feature is particularly advantageous for people with sensitive skin, such as babies and elderly patients.

Figure 1B depicts an exploded view and cross-sectional schematic of the SMP adhesive system. Electronic components for medical monitoring and diagnosis are positioned on the top layer, followed by the SMP layer and a silicone adhesive layer that directly interfaces with the skin. In the initial state ( $T < T_g$ ), the SMP surface is dormant and remains flat, ensuring firm conformal contact with the skin. When the SMP is actuated ( $T > T_g$ ), the SMP recovers its pre-programmed shape, exposing the pyramidal structures on the surface. This topographical transition introduces air gaps at the skin interface, significantly reducing the effective contact area and consequently lowering the force required for peeling. Moreover, the peeling happens across the entire adhesive surface at once, distributing the release stress uniformly rather than concentrating it at a single peeling front. This thermally triggered mechanism facilitates low-force detachment through simple thermal control, minimizing mechanical stress at the skin interface. Figure 1C presents scanning electron microscope (SEM) images of the SMP surface before and after thermal activation. The left image shows the dormant, flat surface corresponding to the initial adhesive state (adhesion ON), whereas the right image clearly exhibits the restored pyramidal structures after thermal stimulation (adhesion OFF). These



**Fig. 1 | Switchable adhesion concept of the SMP adhesive.** **A** Comparison between a conventional bandage (left), which causes noticeable skin irritation after removal, and the SMP adhesive (right), which detaches cleanly. **B** A dormant SMP adhesive in its temporary flat state adhering to skin (left). When heated above its

glass transition temperature ( $T_g$ ), the SMP recovers its programmed pyramidal geometry, enabling self-peeling (right). **C** SEM images showing the adhesive in the “On” state with flat surface (left) and the “Off” state after shape recovery (right).

results confirm that active control of surface morphology via thermal actuation enables strong adhesion during attachment while minimizing irritation during removal. This mechanism makes the SMP adhesive a potential approach for practical bio-interface applications.

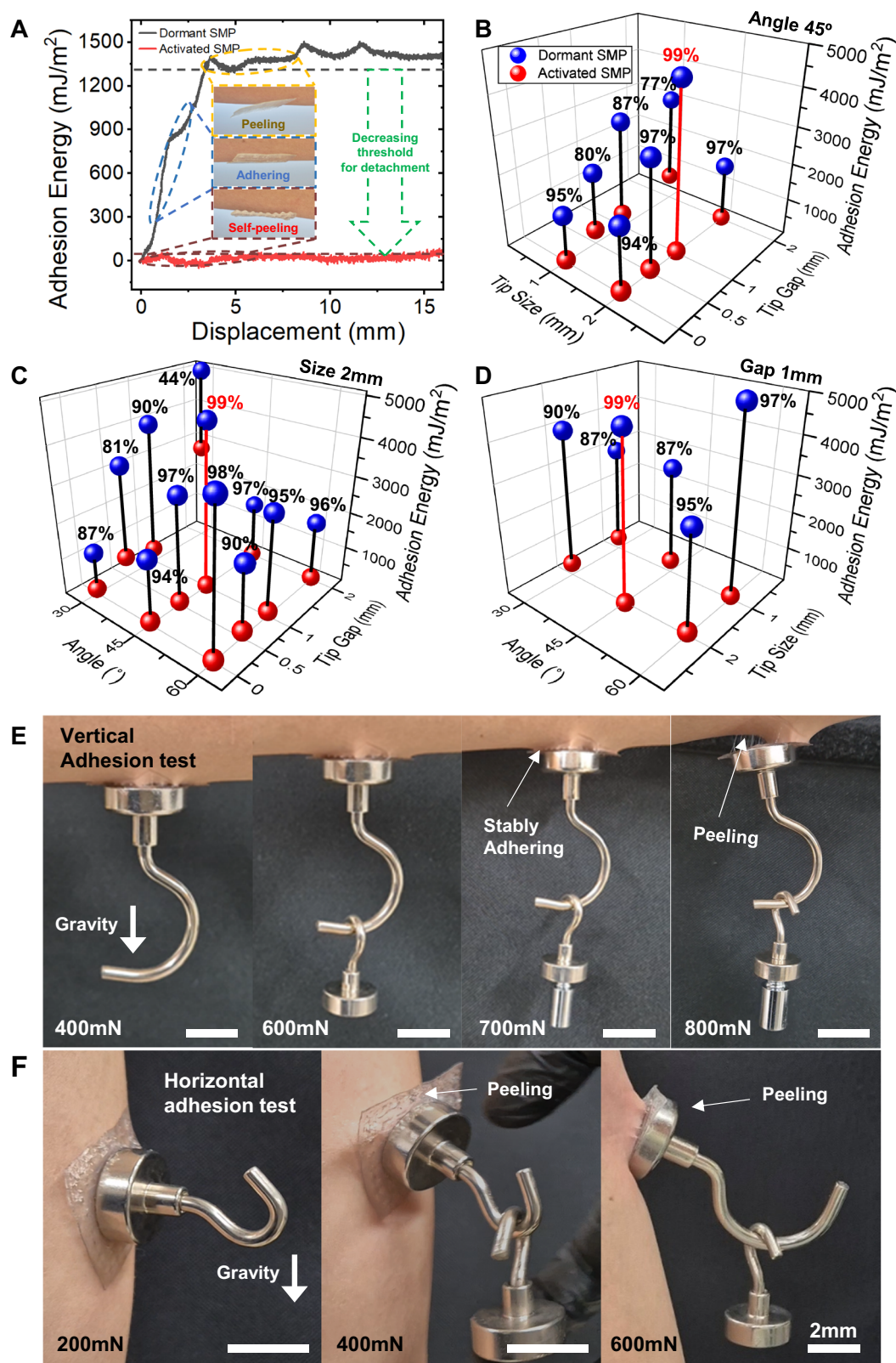
### Structural design optimization and performance of switchable SMP adhesives

One of the key functionalities of the SMP adhesive is its switchable adhesion. The SMP adhesive shows robust adhesion when dormant, but exhibits minimal adhesion, and in some cases even self-peeling, when the SMP is thermally actuated. To quantitatively validate these properties and determine optimal design parameters, mechanical adhesion tests and visual demonstrations were conducted. Figure 2A shows the adhesion energy curves of the SMP in its dormant (adhesion ON) and activated (adhesion OFF) states. Upon thermal activation, the surface transitions from flat to a pyramidal structured topography, resulting in a drastic reduction in adhesion energy. The black curve represents the dormant state ( $T < T_g$ ), exhibiting a high adhesion energy and sustaining loads up to approximately 1300 mJ/m<sup>2</sup>. Under this load, the adhesive remains attached until the energy threshold is reached, at which point peeling initiates. In contrast, the red curve represents the activated state ( $T > T_g$ ), where the adhesion energy sharply decreases to below 200 mJ/m<sup>2</sup>, often causing spontaneous self-peeling. The inset images display the adhesion of dormant SMP and the emergence of the 2 mm-scale pyramidal structures on the sample surface when actuated.

Figure 2B–D visualizes the optimization of adhesion energy as a function of three key structural design parameters, which are tip size, spacing, and angle. These relationships are represented through 3D response maps. The reduction ratio, calculated as

$$(G_{\text{dormant}} - G_{\text{activated}}) / G_{\text{dormant}} \times 100 \quad (1)$$

where  $G_{\text{dormant}}$  and  $G_{\text{activated}}$  represent the adhesion energies before and after actuation, respectively, is presented above each plot in percentage format. Figure 2B shows how adhesion depends on tip size and spacing when the angle is fixed at 45°. Larger tip sizes coupled with larger spacing produced the most pronounced post-activation drop in adhesion energy, in some cases reaching a reduction of up to 99%. Figure 2C evaluates how angle and spacing influence adhesion when the tip size is fixed at 2 mm. The most significant changes were observed at 45° and 60°, particularly for spacing  $\geq 1$  mm, achieving a 95–99% reduction. Figure 2D analyzes angle and tip size when spacing is fixed at 1 mm. The 2 mm tip size consistently exhibited the highest performance, again with the strongest effect at 45° and 60°. These results indicate that sufficiently large structural dimensions and tip angles provide the necessary displacement gradient between the skin and tip apex to effectively relieve adhesion, while a minimum spacing ensures adequate clearance for the dormant tips, thereby enhancing self-peeling efficiency upon activation. Overall, the condition of 2 mm tip size, 1 mm spacing, and 45° angle yielded an optimal -99% reduction in adhesion energy, enabling highly switchable adhesion performance.



**Fig. 2 | Switchable adhesion performance of SMP adhesives and strength demonstrations.** **A** Adhesion energy of the SMP adhesive in dormant and actuated states as a function of displacement. Adhesion energy variations as functions of key structural design parameters: **B** tip size and gap, **C** tip angle and gap, and **D** tip angle

and size. The reduction ratio for each parameter set is shown above the corresponding plot. Adhesion demonstrations on real skin under practical loading conditions, including **(E)** normal loading and **(F)** loading parallel to the adhesive interface.

Figure 2E, F demonstrates the adhesion stability of the system under real skin conditions. Figure 2E and Movie S1 show a vertical adhesion test, where the adhesive supports external loads under gravity. The attachment remains stable under loads up to 700 mN, while gradual peeling initiates at 800 mN. This confirms stable adhesion under normal force conditions. Figure 2F illustrates a horizontal adhesion test, where the gravitational force is parallel to the adhesive surface. Stable adhesion is maintained until peeling initiates at 400 mN, and complete detachment does not occur even at 600 mN. These results confirm that the system can maintain structural reliability for small-scale wearable sensors under practical skin-interfacing conditions. Representative wearable sensors relevant to skin-interfaced physiological monitoring have reported device weights of less than 8 g<sup>38,39</sup>, while the mechano-acoustic (MA) sensing devices demonstrated in the later section of this work weigh 9.8 g and 5.5 g, respectively. Therefore, the measured adhesion strength under both vertical and horizontal loading conditions indicates that the adhesive provides a sufficient safety margin for secure attachment during normal use.

### 3D-DIC characterization and peel-force analysis of SMP adhesive

To investigate the deformation mechanics of the SMP adhesive, 3D-DIC was employed to quantify its thermally induced shape transition on a hot plate over time. The mechanical response was further validated on both a skin phantom and human skin to assess functional adhesion and detachment performance, as described in the “Methods” section. Figure 3A, B presents the temporal evolution of the out-of-plane displacement ( $\Delta z$ ) of the SMP pyramids during heating.  $\Delta z(t)$  was calculated by subtracting the initial z-position  $z(0)$  (prior to thermal stimulation) from the instantaneous z-position  $z(t)$ , respectively. Three samples were compared: i) 30° without the adhesive layer, ii) 60° without the adhesive layer, and iii) 60° with the adhesive layer. At full actuation, the maximum tip displacement reaches approximately 1.15 mm for i) the 30° pyramid (4 × 4 mm base) and ii, iii) 2.5 mm for the 60° pyramid (2.8 × 2.8 mm base). The red regions in Fig. 3B and Movie S2 correspond to large  $\Delta z$  values, creating pronounced height disparities between the pyramid peaks and valleys. These height differences generate air gaps at the adhesive-adherend interface, which contribute to adhesion release upon actuation. Accordingly, case ii) produces a larger out-of-plane displacement than case i), resulting in the formation of a greater interfacial air gap. The addition of an adhesion layer in iii) does not eliminate the height dispersion, allowing interfacial air gaps to persist and thereby facilitating adhesion reduction upon actuation. Moreover, the in-plane displacement ( $\Delta y$ ) behavior with and without the adhesive layer is shown in Fig. S1 and Movie S3. Regardless of the presence of the adhesive layer, in-plane motion persists and contributes to shear-driven separation of the adhesive from the adherend.

The adhesion performance during and after activation was characterized using a tensile tester after adhering the adhesive to a polydimethylsiloxane (PDMS)-based skin phantom with a Young's modulus of approximately 171 kPa. This modulus closely matches that of human dermis, which predominantly governs skin deformation under external loading during attachment and peeling, as strain induced at the surface is largely accommodated within the dermal layer rather than the comparatively thin epidermis<sup>40</sup>. The peel force during detachment (Fig. 3C) and the corresponding surface deformation mapped by 3D-DIC (Fig. 3D and Movie S4) were measured simultaneously, with the analyzed region located approximately 1 mm beneath the surface, comparable to a dermis-relevant depth. In Fig. 3D, green regions indicate negligible deformation, whereas yellow and orange regions correspond to regions subjected to mechanical stimulation, resulting in out-of-plane deformation. In the dormant state, the SMP adhesive exhibited strong adhesion, resulting in higher peel forces and noticeable surface deformation, indicative of mechanical irritation. In contrast, upon thermal activation, the peel force dropped nearly to zero,

accompanied by reduced surface deformation, indicating a lower mechanical load on the underlying substrate. (Fig. S2). The central panel of Movie S4 illustrates the time-dependent evolution of the SMP adhesive during thermal activation, while Fig. S2 presents a representative intermediate frame. These results demonstrate that negligible deformation of the underlying surface is maintained throughout the entire activation process, indicating minimal mechanical irritation during morphing. A similar evaluation on human skin (Fig. 3E, F and Movie S5) confirmed consistent trends. In Fig. 3F, deformation of the curved human skin surface is observed, where blue regions indicate displacement in the negative z-direction and red regions indicate displacement in the positive z-direction in response to applied mechanical stimulation. The dormant SMP required greater peeling force than the activated one, matching the phantom-skin results. Slightly lower peel loads were recorded due to natural skin curvature, microtexture, and hair, but the activated SMP still detached smoothly with negligible deformation of surrounding tissue. These findings collectively validate the SMP adhesive's reversible adhesion mechanism and its ability to minimize skin irritation through thermally triggered detachment.

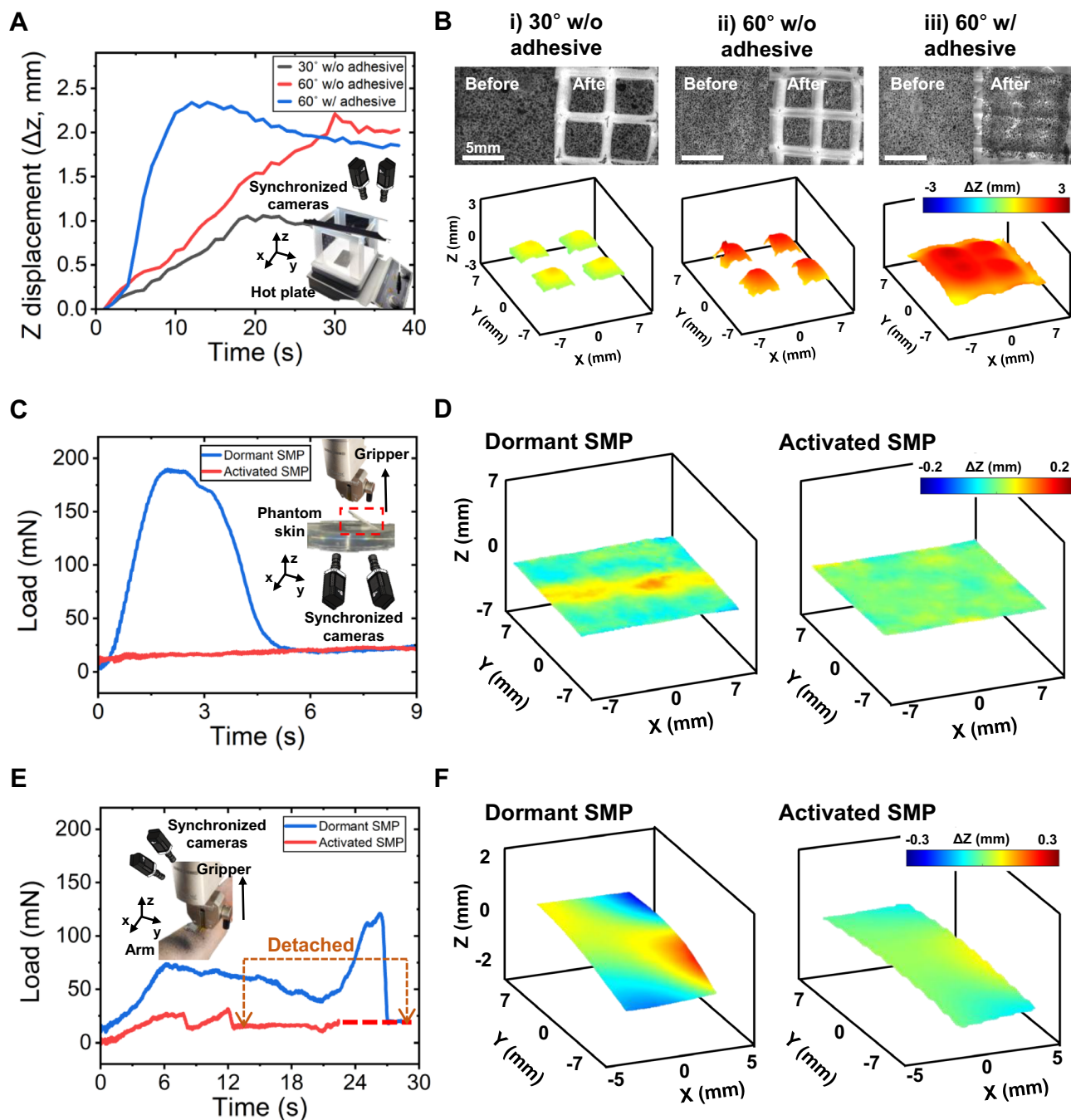
### Kirigami-enhanced conformability and breathability of the SMP adhesive

To achieve conformal attachment to highly curved body sites and facilitate efficient sweat evaporation, we designed an SMP adhesive incorporating a kirigami structural topology and systematically evaluated its performance. Figure 4A shows SEM images of the kirigami-patterned SMP. The inset image illustrates the SMP adhesive in its dormant state, where the cut lines remain open and well maintained. This architecture provides markedly greater mechanical compliance compared to the non-kirigami SMP, enabling large deformation without detachment.

Figure 4B compares the bending stiffness, expressed as force over deflection, of non-kirigami and kirigami SMP structures as a function of thickness. The bending stiffness was calculated by measuring the slope of the Force vs Deflection curves for the various thickness samples, as shown in Fig. S3. For the same thickness, the kirigami SMP exhibits higher extensibility and undergoes substantial deformation under minimal load. The kirigami design maintains low bending stiffness even at 400  $\mu$ m thickness, demonstrating that excellent flexibility and compliance can be achieved without increasing fabrication complexity. The triangular regions labeled A and B correspond to the minimum design requirements for adapting to moderate curvature surfaces and highly curved surfaces, as shown in Fig. 4C, D respectively.

Figure 4C displays the attachment of SMP adhesives on body sites with moderate curvature, such as the thumb and bent wrist. In this case, a non-kirigami SMP with a thickness of 170  $\mu$ m was used because it provides sufficiently low bending stiffness for these geometries, which corresponds to region A in Fig. 4B. However, achieving conformal attachment on highly curved surfaces such as the pinky finger, bent arm, or earlobe requires bending stiffness within region B of Fig. 4B, which is difficult to attain with non-kirigami structures because they are challenging to fabricate reliably at thicknesses below 100  $\mu$ m. Therefore, as shown in Fig. 4D, the kirigami SMP was used to apply the SMP adhesive even in the highly curved areas. Despite the similar thickness as the non-kirigami SMP used in Fig. 4C, it demonstrates excellent structural flexibility and skin conformability, enabling secure attachment even in highly curved regions. Upon actuation, the kirigami SMP undergoes shape recovery and spontaneously unwraps from curved surfaces, as shown in Movie S6.

The kirigami SMP described above demonstrated excellent adhesion on highly curved regions, but the applicable body sites were primarily limited to surfaces with single-axis curvature. To further expand applicability to doubly curved anatomical regions such as the elbow and nose, we fabricated a 2-way kirigami SMP, as shown in



**Fig. 3 | Mechanical analysis of the SMP adhesive.** **A** Time-dependent peak height change ( $\Delta z$ ) of the SMP patch during heating, with the inset showing the 3D-DIC/hot-plate experimental setup used to measure the SMP shape morphing process. **B** Raw image sets of the SMP patches with 30°, 60°, and 60° (with the adhesive layer) before and after activation (top) with the corresponding 3D-DIC deformation maps after activation; the color bar represents  $\Delta z$ . **C** Tensile load versus time for dormant and activated SMP patches adhered to phantom skin, with the inset

showing the 3D-DIC/tensile experimental setup on phantom skin. **D** Surface deformation distributions during the tensile test for dormant and activated SMP patches on phantom skin. **E** Tensile load versus time for SMP patches on human skin, with the inset showing the 3D-DIC/tensile testing setup on human skin. **F** Surface deformation distributions during the tensile test for dormant and activated SMP patches on human skin.

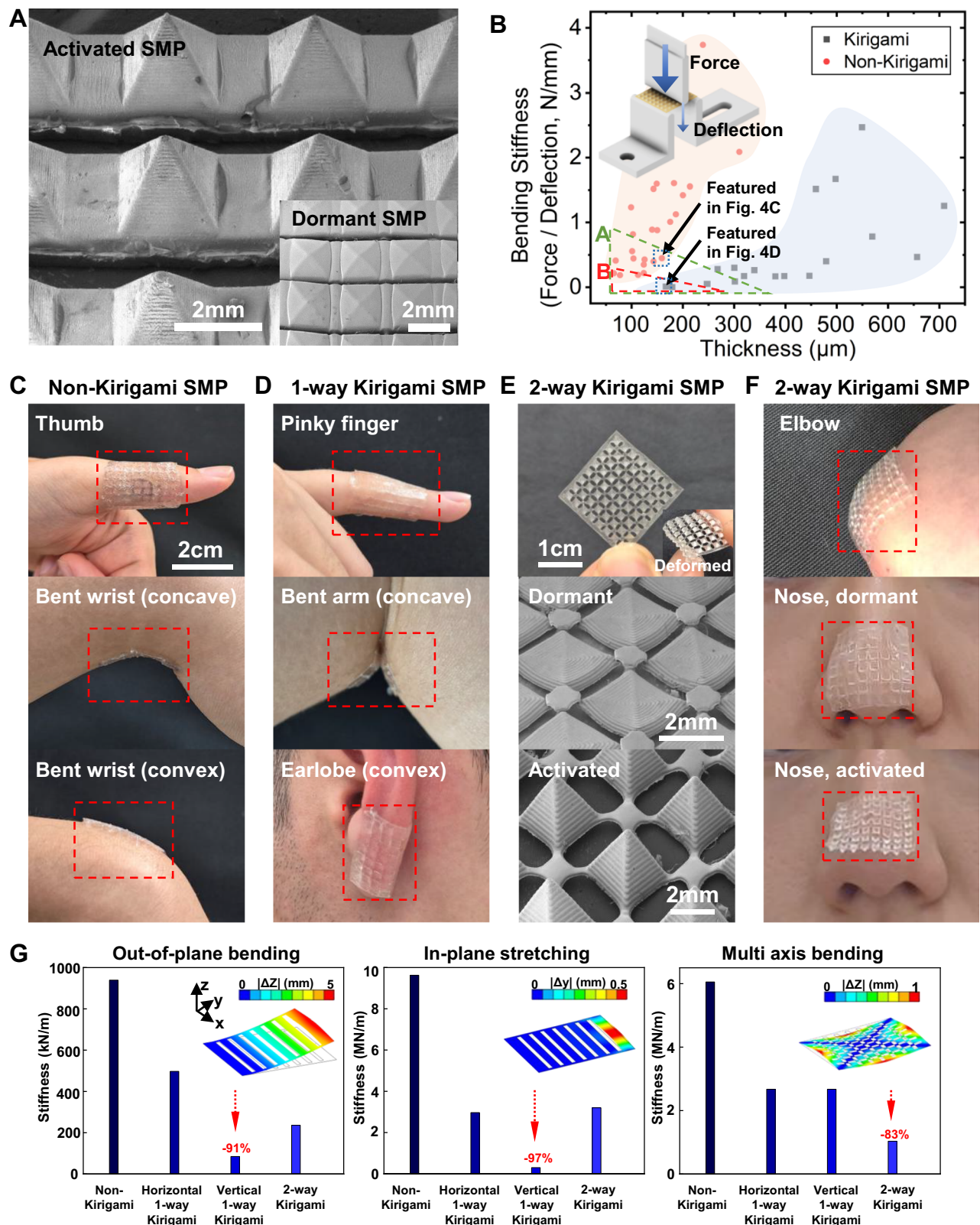
Fig. 4E. In this design, slit patterns were introduced in two orthogonal directions while preserving the corner regions, as shown in the SEM images. Figure 4F presents demonstrations of conformal attachment in the dormant state on the elbow and nose, followed by spontaneous self-peeling after thermal activation.

Figure 4G and Fig. S4A further examine the mechanical role of the kirigami geometry using finite element analysis. The non-kirigami original SMP patch without kirigami cuts, the 1-way kirigami design, and the 2-way kirigami design were compared under representative

deformation modes, including out-of-plane bending, in-plane stretching, and multiaxial saddle-like bending. The reaction-force-based effective stiffness,

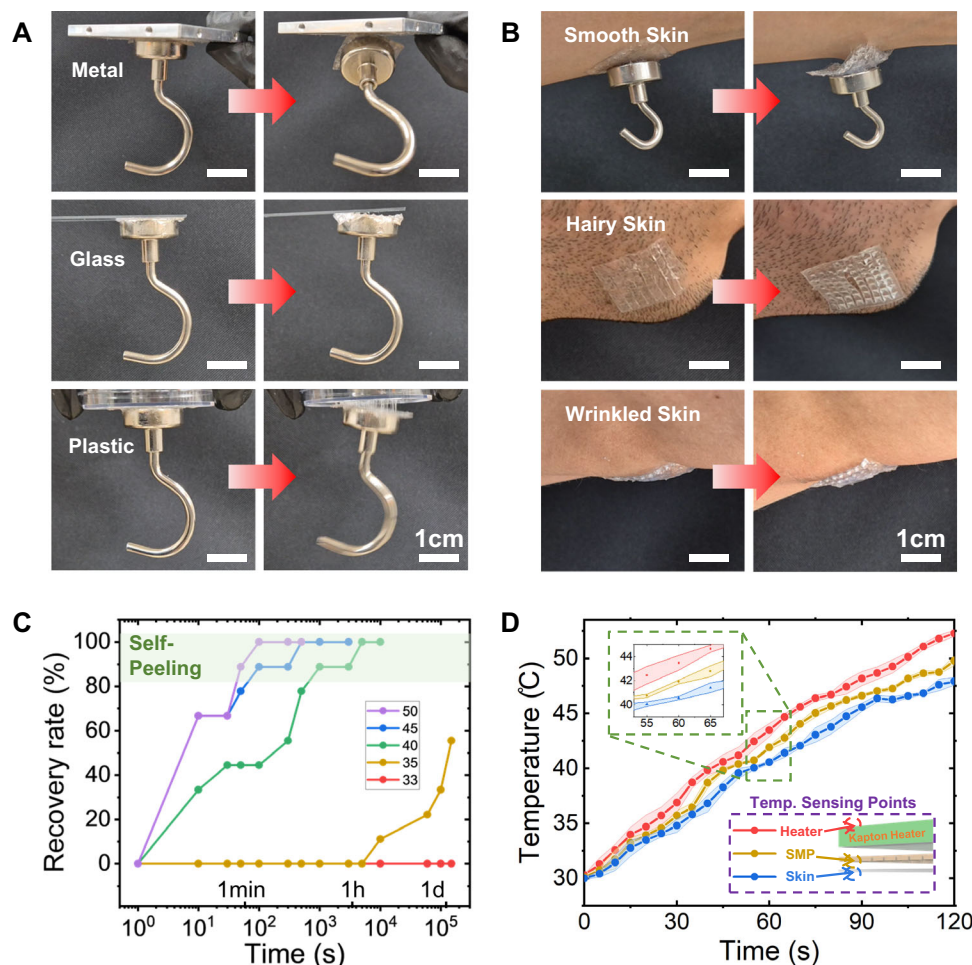
$$k_{\text{eff}} = F_{\text{reaction}} / \delta \quad (2)$$

was used to quantify the compliance of each structure. Compared with the original patch, the 1-way kirigami design reduced  $k_{\text{eff}}$  by approximately 91% under out-of-plane bending and 97% under in-



**Fig. 4 | Bending stiffness and FEA of a kirigami SMP adhesive.** **A** SEM image of the switchable kirigami SMP adhesive. **B** Flexural force per displacement measurements, representing bending stiffness, as a function of adhesive thickness. **C** Adhesion performance on moderately curved body sites using a non-kirigami SMP adhesive sheet. **D** Adhesion on highly curved body sites enabled by the

kirigami SMP adhesive. **E** Photographs and SEM images of the 2-way kirigami SMP. **F** Adhesion and self-peeling behavior on doubly curved anatomical regions. **G** Effective stiffness ( $k_{\text{eff}}$ ) of each design under various loading conditions. The inset displacement maps show the corresponding deformation modes for the cases with the largest stiffness reduction.



**Fig. 5 | Adhesion of SMP adhesives on diverse surfaces and their temperature-dependent behavior.** **A** Adhesion performance of the SMP adhesive on metal, glass, and plastic substrates. **B** Adhesion on various skin types, including smooth,

hairy, and wrinkled skin. **C** Recovery rate of the SMP adhesive as a function of time under different applied temperatures. **D** Temperature profiles over time measured at each interfacial layer of the adhesive.

plane stretching, while the 2-way kirigami design reduced  $k_{\text{eff}}$  by approximately 83% under multiaxial saddle-like bending. These results indicate that the 1-way kirigami design is effective for directional deformation, whereas the 2-way kirigami design provides enhanced compliance under multidirectional deformation.

To experimentally compare bending accommodation, controlled bending deformation was applied to the original SMP patch and the 1-way kirigami SMP patch by varying the contact angle using a tensile tester. Figure S4B presents reconstructed raw images, normalized out-of-plane displacement profiles ( $w$ ), and curvature profiles ( $\kappa$ ) along the selected centerline. The 1-way kirigami patch exhibits larger out-of-plane deformation than the original patch, and  $\kappa_{\text{mean}}$  increases from 0.028 to 0.050, corresponding to an approximately 78.6% increase. This result experimentally confirms that the 1-way kirigami design accommodates bending over a larger portion of the structure.

Figure S5 evaluates the water vapor transmission behavior of the kirigami SMP to assess its suitability for long-term wear under perspiration-prone conditions. The moisture loss rate was measured over time at 40% relative humidity under two temperature conditions: 20 °C (ambient) and 36.5 °C (skin temperature). A higher moisture loss rate indicates superior vapor permeability, which corresponds to better breathability and wearer comfort. Under both thermal conditions, the kirigami SMP exhibited the highest moisture loss rate compared to Ecoflex, a non-kirigami SMP sheet, and a conventional medical adhesive bandage. The schematic on the right illustrates the moisture release mechanism through the kirigami openings. Superior

water vapor permeability makes it highly suitable for prolonged use by effectively preventing sweat accumulation.

### Adhesion demonstration on various surfaces and thermal mechanics of SMP adhesives

To validate the practical applicability of the SMP adhesive, we evaluated its adhesion performance across various material surfaces and skin conditions, analyzed its shape recovery behavior as a function of time and temperature, and investigated temperature gradients during activation. Figure 5A and Movie S7 present the adhesion and thermally-triggered peeling behavior of the SMP adhesive when applied to non-skin surfaces, including metal, glass, and plastic. The SMP adhesive exhibited stable attachment in the dormant state across all substrates and reliably self-peeled upon thermal activation with only the weight of the metal hook, demonstrating strong material versatility. Figure 5B and Movie S8 show adhesion performance on human skin under three representative conditions: smooth skin, hairy skin, and wrinkled skin. In all cases, the adhesive maintained conformal attachment in the dormant state and underwent clean detachment upon thermal activation. Although adhesion strength was slightly weaker on rough or uneven skin textures, the adhesive consistently maintained reliable contact across all tested skin types.

Figure 5C quantitatively characterizes the shape recovery rate and temperature-dependent recovery dynamics of the SMP adhesive. The graph compares recovery behavior over time at different temperatures (50 °C, 45 °C, 40 °C, 35 °C, 33 °C). Here, the recovery rate is

defined as the ratio of the current pyramid height to the original pyramid height before programming, expressed as a percentage. At temperatures above 45 °C, the SMP recovered more than 90% of its programmed geometry within only 2 min. When the recovery rate surpasses 90%, the array of pyramids initiates simultaneous self-peeling over the entire SMP adhesive area. At 35 °C, the SMP remained fully dormant for 1 h and then gradually restored half of its programmed shape after one full day. In contrast, no deformation occurred at 33 °C, which corresponds to actual skin temperature, confirming that the pyramidal structure remains mechanically dormant and supports the possibility of long-term wear for skin-interfaced devices.

Thermal safety is a critical consideration for skin-mounted applications. Previous studies have reported that skin exposure at 44 °C requires approximately 6 h to induce thermal burns, while temperatures between 45 °C and 50 °C require exposure durations ranging from several hours to several minutes<sup>41</sup>. Although prolonged exposure near 45 °C may eventually cause thermal injury, short-term thermal contact is generally considered safe. In our system, the SMP structures fully recovered within approximately 2 min at 45 °C and within 1 min at 50 °C, resulting in exposure durations substantially shorter than reported safety thresholds. These results indicate that the duration and temperature required for activation are substantially below reported thermal injury conditions, thereby reducing the risk of thermal discomfort and low-temperature burns. For applications requiring lower-temperature activation, full recovery can also be achieved at 40 °C with a longer activation time of approximately 17 min.

Figure S5D presents the temperature evolution across each interfacial layer of the SMP adhesive during heating, confirming that sufficient shape recovery occurs without creating risk of thermal damage to the skin. The inset schematic identifies the three measurement locations, which correspond to the region of the heater, the SMP layer, and the skin. The inset magnified plot highlights the temperature difference among these points, showing that the SMP layer reaches approximately 44 °C, which enables complete recovery of the pyramidal structures, while the skin-facing region remains below 41 °C. This temperature separation ensures safe and comfortable activation for controlled peeling. On the other hand, in the case of SMP adhesive without pyramid structure, there is little difference in thickness due to pyramid structure recovery, indicating the possibility that the heater temperature can be exposed to the skin as it is (Fig. S6).

### Wireless mechano-acoustic sensing for evaluating SMP adhesive performance

The performance of the SMP adhesive was evaluated using two representative MA sensing systems: the Broadband Acousto-Mechanical Sensing (BAMS) device<sup>42</sup> and the Miniaturized MA cough sensor<sup>43</sup>. As shown in Fig. 6A, normalized MA signals from the BAMS device were recorded during various physical activities using three types of adhesives: a commercial adhesive (blue), a dormant SMP (black), and a thermally activated SMP adhesive (red). The commercial and dormant SMP adhesives exhibited comparable signal amplitudes and stability, whereas the activated SMP adhesive showed pronounced signal attenuation due to mechanical softening and partial detachment at the skin-device interface. During low-intensity activities (up to ~60 s), the activated SMP produced minimal measurable signals. Under higher intensity motions, such as jumping, complete detachment occurred at approximately 110 s. In this regime, reduced adhesion allowed relative motion between the device and the skin, resulting in secondary motion artifacts superimposed on the primary body-induced acceleration signals, as evident in the red sharp peak in Fig. 6A. These observations are further supported by immediate activation states shown in Figs. S7A–D which present representative normal-breathing data acquired during the SMP transition process. Figure S7A corresponds to an early transition state (~2 min of thermal

stimulation), in which the SMP adhesive is partially actuated and intermittently detached. In this regime, breathing-induced MA signals remain detectable, albeit with reduced amplitude compared to dormant conditions. Figure S7B represents a more advanced activation state (~7 min total stimulation), where increased pyramid formation leads to greater lift-off from the skin and further attenuation of MA amplitude, indicating weakened mechanical coupling. Corresponding Short-Time Fourier Transform (STFT)-based spectrograms of respiratory and cardiac sounds (Fig. S7C, D) show a progressive reduction in spectral intensity from state A to B, confirming gradual loss of acoustic coupling as activation proceeds toward the fully actuated state (Fig. 6).

Figure 6B, C displays spectrograms of respiratory and cardiac sounds obtained from microphone data. Yellow regions indicate high-intensity physiological signals, whereas darker colors correspond to reduced signal intensity. Both the commercial and dormant SMP adhesives yielded consistent frequency responses and spectral amplitudes, while the activated SMP exhibited significantly reduced spectral intensity, confirming effective decoupling at the skin-device interface.

High-frequency MA signals associated with vocal-induced motions<sup>43</sup>, including coughing, throat clearing, and vocalization, were recorded using the MA cough sensor (Fig. 6D). Fourier power-spectral analysis (Fig. 6E) confirms that cough signals are clearly captured prior to activation but become substantially attenuated after thermal activation. In these spectrograms, yellow regions highlight intervals of strong physiological activity. Notably, the dormant SMP produced slightly larger signal amplitudes than the commercial adhesive, which is attributed to its higher effective stiffness and enhanced vibration transmission.

Collectively, these results demonstrate that the SMP adhesive provides sensing performance comparable to, or exceeding, that of conventional commercial adhesives during physiological motions, while enabling near-complete detachment and signal suppression upon activation. This dual functionality, robust sensing in the dormant state and controllable release upon activation, highlights the potential of SMP adhesives for next-generation skin-interfaced biomedical devices requiring on-demand removability and reduced stress concentration.

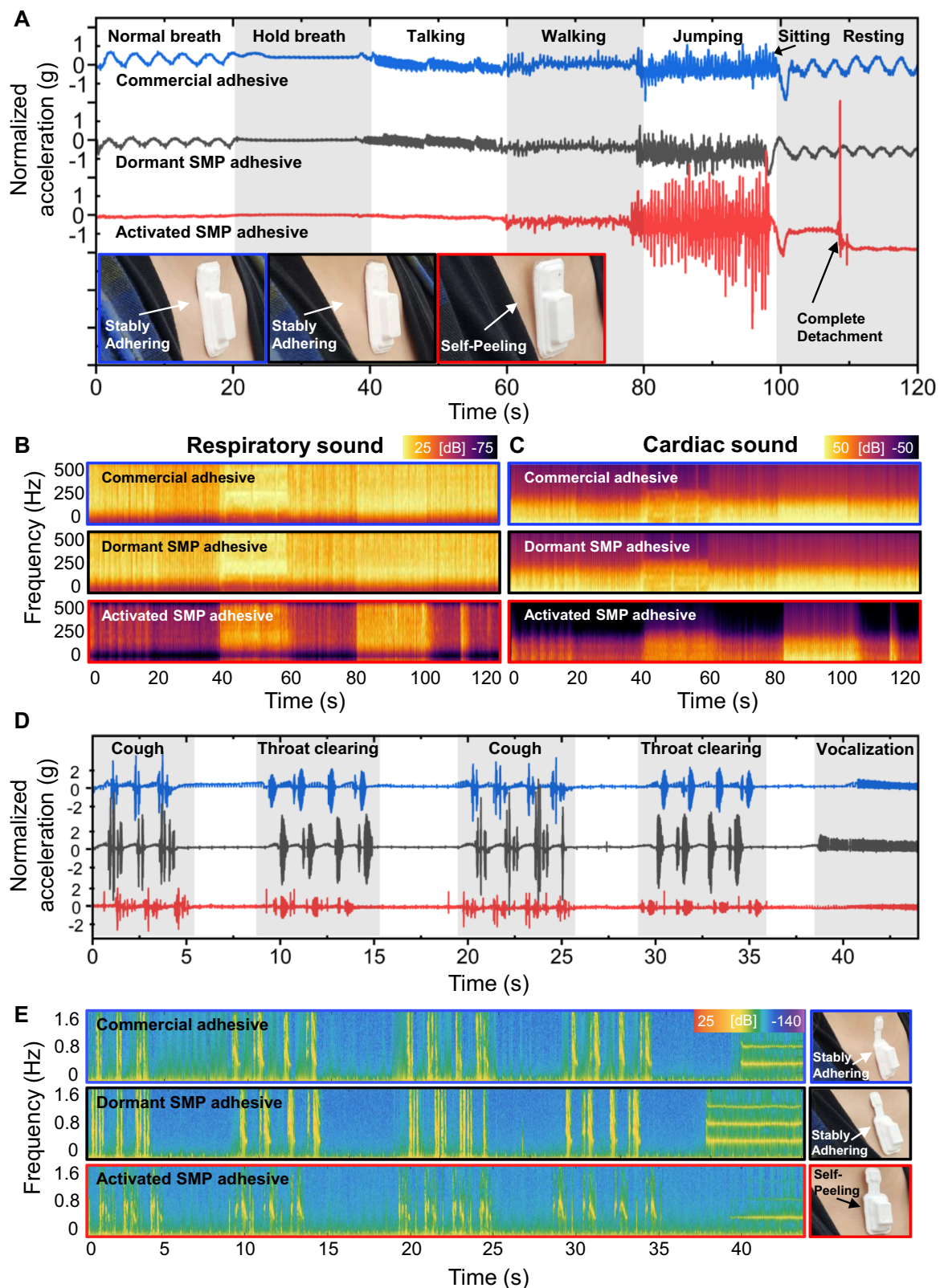
## Discussion

This work presents a thermally triggered SMP adhesive that combines strong on-skin attachment with on-demand detachment, with suppressed interfacial stress concentration through programmable pyramidal structure recovery. The geometry-driven adhesion switching mechanism enables a large reduction in adhesion energy upon activation while maintaining stable adhesion during use. 3D-DIC confirms that thermal actuation suppresses interfacial stress concentrations and minimizes subsurface skin deformation during peeling, addressing a key limitation of conventional medical adhesives. The incorporation of a kirigami architecture further enhances conformability and breathability on curved, perspiration-prone body sites. Compatibility with wireless mechano-acoustic sensing devices demonstrates practical utility for skin-interfaced electronics. Together, these results demonstrate the potential of this adhesive platform for wearable and biomedical devices requiring reliable attachment and gentle, controlled removal.

## Methods

### Fabrication of the SMP adhesive

As shown in Fig. S8A, the SMP adhesive developed in this study consists of a bilayer structure composed of an SMP layer and a silicone adhesive layer. First, a pyramidal-patterned 3D-printed resin mold (White Resin, Form 4L, Formlabs, USA) was prepared as the positive master mold. PDMS (Sylgard 184, Dow Corning Corp., USA) was then cast over the master to produce the negative mold. Next, the SMP



**Fig. 6 | Skin-interfaced wireless wearable devices using the SMP adhesive to mitigate skin irritation.** **A** Comparison of representative mechanical acceleration data from the BAMS device using commercial (blue), dormant SMP (black), and activated SMP (red) adhesives, recorded over a 120 s interval as an individual performs various activities, including breathing, breath-holding, talking, walking, jumping, sitting, and resting. The inset shows photographs of each adhesive condition with the device attached. **B** Respiratory and **C** cardiac sound spectrograms

obtained from the microphone data of the BAMS device during the same activities corresponding to **(A)**. **D** Comparison of representative acceleration data from the MA cough sensor using commercial (blue), dormant SMP (black), and activated SMP (red) during various vocal activities, including coughing, throat clearing, and vocalization. **E** Fourier power spectrograms of acceleration data from the MA cough sensor during these vocal activities, with accompanying illustrations of each adhesive condition on a test subject.

precursor was synthesized using the procedure detailed below<sup>44</sup>. EPON 826 (diglycidyl ether of bisphenol A epoxy monomer; Hallachem, Korea), E1075 (poly(bisphenol A-co-epichlorohydrin); Sigma-Aldrich, USA), and Jeffamine D230 (poly(propylene glycol)bis(2-aminopropyl); Hallachem, Korea) were mixed at a weight ratio of 1:0.94:0.837. EPON 826 and E1075 were first liquefied at 120 °C, followed by the addition of Jeffamine for curing. The resulting SMP mixture was cast onto the PDMS negative mold to form the positive pyramidal structured SMP layer. After curing, the SMP layer was flat-pressed at 120 °C and cooled. A silicone adhesive layer (Ecoflex gel, Smooth-On, Inc., USA) was then applied by spin-coating at 2500 rpm for 30 s. The adhesive layer was optimized to have a thickness of 30 µm (Fig. S9). This programming step was completed during device fabrication to generate the high-adhesion (“on”) state prior to use, and the pre-programmed adhesive was subsequently applied to the skin without additional heating or compression.

### Fabrication of the kirigami SMP adhesive

For the kirigami SMP adhesive, slit cuts were manually introduced into the SMP layer using a razor blade before the flat-pressing step (Fig. S8B). The remaining fabrication steps were identical: the patterned SMP was flat-pressed at 120 °C and cooled, then coated with a silicone adhesive layer by spin-coating at 2500 rpm for 30 s. The kirigami SMP adhesive provides a modular adhesive-level platform in which the geometry, size, and spacing of the openings can be tailored to specific wearable-device layouts. When integrated with breathable or perforated electronics, these openings can be aligned with corresponding device features to support system-level breathability.

### Fabrication of the phantom skin

A compliant skin phantom was prepared using PDMS (Sylgard 184, Dow Corning) by mixing the base and curing agent at a mass ratio of 20:1. To reduce the elastic modulus to a skin-relevant range, silicone thinner (Smooth-On) was added at 50 wt% relative to the PDMS mixture. After mixing, the ingredients were cast into a Petri dish, degassed under vacuum for 30 min to remove trapped air, and thermally cured at 85 °C for 24 h.

### Adhesion energy measurement during 90° peeling test

Adhesion energy was quantified using a 90° peeling test (Fig. S10). The setup consisted of an aluminum gripping fixture attached to a load cell (GS0-25; Transducer Techniques, USA), vertically actuated by a linear stage (VT-80; Physik Instrumente, Germany). A synthetic skin substrate (Ecoflex 0050, Smooth-On, Inc., USA) was laterally displaced at 1 mm/s using a horizontally moving linear stage (VT-80; Physik Instrumente, Germany), continuously recording its peel strength with the SMP adhesive.

### Flexural characterization of kirigami and non-kirigami SMP

The flexural properties (bending stiffness) of the kirigami SMP were evaluated using a universal testing machine (UTM; LSI, Ametek Inc., USA). A custom jig for sample fixation was fabricated using a 3D printer (Form 4L, Formlabs, USA), as shown in Fig. S11. The loading head was lowered at a speed of 10 mm/min, and force–deflection data were recorded using NEXYGEN Plus 3.0 software (Ametek Inc., USA).

### Finite element analysis of kirigami-enabled mechanical compliance

Finite element analysis was performed using the Static Structural module in ANSYS Mechanical (ANSYS Inc., USA) to evaluate the mechanical compliance of kirigami-patterned SMP patches. The SMP patch was modeled as a 20 mm × 20 mm shell/surface body with a slit width of 1.25 mm and discretized using SHELL181 elements. The SMP was treated as a linear elastic isotropic material with a Young's modulus of 2.5 GPa<sup>45</sup> and a Poisson's ratio of 0.4<sup>46</sup>. Static structural

simulations were conducted with large deformation enabled and solved using a sparse direct solver. As shown in Fig. S12, for the single-axis loading cases, one edge of the patch was fixed, and a prescribed point displacement was applied at the center of the opposite edge in the corresponding loading direction; the imposed displacement was defined as  $\delta$ , and the resulting reaction force was used to calculate effective stiffness. For multiaxial saddle-like bending, the edge of the central kirigami opening was fixed, and prescribed displacements were applied at four points to generate multiaxial deformation. The imposed displacement was ramped over 50 substeps, and the corresponding reaction force was extracted to calculate the effective stiffness,  $k_{eff} = F_{reaction} / \delta$ .

### Water permeability test

Water vapor transmission was measured using a constant temperature and humidity chamber (1111801-020-00-303, SYSTRONICS, Korea) under two temperature conditions, 36.5 °C and 20 °C, at 40% relative humidity. The percentage of weight loss due to water evaporation was monitored over time.

### Temperature distribution measurement

The temperature distribution across each layer of the SMP adhesive was recorded using K-type thermocouples connected to a K thermocouple controller (XY-WT04, Xinxiang Chaosheng Electric Equipment Co., Ltd., China). Thermocouples were embedded at each layer, and measurements were repeated 5 times under 4 V heating using a Kapton heater (KHR 12 V 6.6 W Ø29, heater rising, Korea). The recorded temperature values were then processed statistically.

### Experimental protocol for 3D-DIC measurement of SMP adhesive actuation and peel mechanics

Three independent sets of 3D-DIC experiments were conducted to characterize (1) the thermally induced deformation of the SMP adhesive itself, (2) the deformation of a PDMS-based skin phantom during detachment, and (3) the deformation of human skin during detachment. Each experiment was performed to capture full-field 3D displacements during actuation and peeling under realistic mechanical conditions.

All 3D-DIC experiments were recorded using two synchronized high-speed cameras (resolution: 2049 × 712 pixels, frame rate: 50 fps) positioned symmetrically with respect to the sample normal to enable stereo reconstruction. Approximately 3,000 sequential frames were captured per case, corresponding to the full duration of actuation and detachment. Image sequences were processed using the open-source MultiDIC software<sup>47</sup>, which allows subpixel accuracy in 3D reconstruction and displacement tracking.

The DIC parameters were set to ensure high-resolution and accurate wave-displacement characteristics: subset radius = 21 pixels, subset spacing = 3 pixels, and iteration cutoff = 50. The resulting root-mean-square error of 3D reconstruction was less than 60 µm for all experiments. A tensile tester (MARK-10 FS05-20) was operated simultaneously in all mechanical validation tests using the experimental setup shown in Fig. S13 to synchronize load and displacement measurements with the DIC acquisition.

For large-scale SMP samples, square precursors (5 × 5 mm) were designed with pyramid apex angles of 30° and 60°, both with and without an adhesive layer. The samples were fixed on a hot plate, and heating was initiated from the bottom surface while continuously recording deformation for 40 s using the 3D-DIC system. The time-dependent  $\Delta z$  fields were reconstructed over the entire patch to visualize the shape-morphing process. For quantitative comparison,  $\Delta z$  values from the four pyramid tips were averaged at each time step and plotted as a function of time (Fig. 3A). The same procedure was repeated for all combinations of apex angles and adhesive conditions to assess the effect of geometry and interfacial compliance and actuation dynamics.

The second experiment quantified both peel load and the sub-surface deformation of the skin phantom directly beneath the SMP adhesive during detachment. The SMP adhesive (small-scale version,  $2 \times 2$  mm pyramid base, array of  $8 \times 8$ ) was attached to a transparent PDMS phantom with a Young's modulus of  $\sim 171$  kPa, comparable to that of human dermis. A thin layer of black speckles was embedded at a subsurface plane  $\sim 1$  mm below the surface to track deformation at a dermal-thickness scale, while avoiding direct contact between the speckle pattern and the SMP adhesive during peeling. The tensile tester gripper was attached to the top of the SMP patch, and the sample was pulled vertically upward (1 mm/s) for 10 s. Both high-speed cameras were positioned below the phantom to image through the transparent substrate, capturing deformation of the underlying surface in real time. The 3D investigation volume was approximately  $13 \times 13$  mm<sup>2</sup>, sufficient to cover the entire SMP adhesive and the adjacent phantom region. The synchronized load-displacement data and 3D deformation fields enabled precise correlation of mechanical force and local strain evolution during detachment.

In the third experiment, the SMP adhesive identical to the second experiment was directly attached to human skin (volar forearm) using gentle manual pressure. The patch was connected to the gripper of the same tensile tester and peeled vertically at a constant rate of 1 mm/s for 30 s. Simultaneous force and 3D deformation data were acquired using two synchronized cameras viewing the region around the SMP patch. The 3D investigation area covered approximately  $8 \times 12$  mm<sup>2</sup>, focusing on the immediate periphery of the adhesive interface to quantify strain propagation into the surrounding tissue. A removable black speckle pattern was applied around the attachment site using medical-grade skin-safe ink. The 3D deformation maps revealed the skin's local response during both dormant and thermally activated detachment conditions.

### Procedures for wireless mechano-acoustic measurements on skin

MA validation of the SMP adhesive was performed using two independent wireless sensing systems: a BAMS device and a Miniaturized MA cough sensor. Both platforms employ tri-axial inertial sensing and wireless data transmission for continuous monitoring of skin vibrations associated with physiological and vocal activities.

The BAMS device comprised five functional modules: dual microphones (ICS-40180, TDK), a tri-axial inertial measurement unit (IMU; LSM6DSL, STMicroelectronics), flash memory (2GB; MT29F2G, Micron), a Bluetooth system-on-chip (ISP-1807, Insight SIP), and hardware for power management and wireless charging. The MA cough sensor integrated two IMUs for redundancy and artifact rejection, each capable of tri-axial accelerometry and angular-velocity measurements.

Each device was attached to the anterior neck region of a healthy participant ( $n = 3$ , age 24 years) using three adhesive conditions: (1) commercial acrylic adhesive (2477P-4-10, 3M), (2) dormant SMP adhesive (room temperature), and (3) thermally activated SMP adhesive (post-heating). For each condition, the participant completed a standardized activity sequence: normal breathing, breath-holding, talking, walking, jumping, sitting, and resting, with each activity lasting 20 s. Additional recordings were obtained for coughing, throat clearing, and vocalization, each lasting 5 s.

All experiments were performed on the same participant under identical environmental conditions. For each adhesive type, three repeated measurements were conducted to ensure reproducibility. Thermal activation of the SMP adhesive was induced using a commercial disposable heat pack (average surface temperature  $55^\circ\text{C}$ ). To minimize potential effects from residual adhesive or skin-surface contaminants between trials, the test area was cleaned thoroughly with 70% isopropyl alcohol swabs following each detachment event, followed by a 10-min rest interval before initiating the next measurement.

The BAMS device simultaneously acquired microphone data at 1 kHz and IMU acceleration data at 104 Hz. The MA sensor recorded tri-axial acceleration at 1.6 kHz for z-axis signals and 30 Hz for x- and y-axes. Internal temperature sensors were integrated into the IMUs, and the system-on-a-chip provided die temperature measurements during all trials. All signals were time-stamped and synchronized via internal clocks, then transmitted wirelessly to a receiver.

Raw acceleration and acoustic signals were band-pass filtered (0.5–500 Hz) to remove baseline drift and high-frequency noise. Spectral analyses were performed using STFT with 512-sample Hamming windows with 75% overlap. Respiratory (150–450 Hz) and cardiac (10–150 Hz) components were extracted from body-facing microphone data via digital band-pass filtering, and their time-frequency characteristics were visualized using STFT-based spectrograms. IMU acceleration data were similarly transformed into the time-frequency domain to identify dominant motion frequencies. All raw signals were preprocessed and scaled into consistent physical units (g or ADC counts) using standardized calibration procedures.

### Ethics

All procedures involving human participants were conducted in accordance with relevant institutional and national ethical regulations. The study protocol, "Dynamic Analysis of a Device Through Visualization and Signal Measurement," was reviewed by the Pohang University of Science and Technology (POSTECH) Institutional Review Board and was determined to be exempt from IRB review (exemption no. PIRB-2025-E046). Written informed consent was obtained from the participant before participation in the study. All on-skin experiments, including human-skin peeling, conformability demonstrations, and mechano-acoustic measurements, were conducted on the same healthy adult participant.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

### Data availability

All data supporting the findings of this study are available within the article and its supplementary files. Any additional requests for information can be directed to and will be fulfilled by the corresponding authors. Source data are provided with this paper.

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## Author contributions

C.S., K.R.J. and C.L. conceived the idea. C.S., U.K. and H.J. designed the study, conducted experiments, and analyzed data. U.K. synthesized and fabricated the SMP adhesives, optimized the pyramid geometry, and conducted the SEM characterization. H.J. performed the 3D-DIC experiments and finite element analysis. U.K. and H.J. integrated the SMP adhesives with the wireless mechano-acoustic sensing devices and

conducted the measurements. J.Y.K. and M.-S.J. fabricated the BAMS and miniaturized MA cough-sensing devices. J.K. and U.K. fabricated the adhesion-energy measurement setup and conducted the measurements. C.S., U.K., and H.J. wrote the manuscript. All authors read and revised the manuscript. C.S., J.A.R., S.K., and J.-T.K. supervised the work.

## Competing interests

The authors declare no competing interests.

## Additional information

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