



Smart Mechanical Structures and Design for Advanced Adhesives: A Review

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Abstract

Smart adhesives with engineered mechanical structures have emerged as a transformative technology with broad applications in fields such as wearable healthcare devices, bioengineering, and soft robotics. By integrating advanced mechanical architectures like kirigami, tessellations, and multilayered designs, these adhesives exhibit enhanced surface and mechanical properties that lead to superior interfacial adhesion. Such designs offer critical advantages—improved stretchability, substrate conformability, and increased adhesion strength—over conventional adhesives. This review explores the range of engineered structures used in smart adhesives and demonstrates how these innovations address the limitations of traditional adhesives. Additionally, we discuss their applications in wearable healthcare devices, flexible electronics, and robotics.

Keywords Smart adhesive · Engineered mechanical structure · Kirigami · Tessellation · Multilayer adhesive

1 Introduction

Smart adhesives are becoming increasingly essential in advanced technologies such as wearable electronics, soft robotics, and precision manufacturing [1–10]. These applications demand adhesives that not only provide strong and

tunable adhesion but also offer additional features such as reversibility, minimal surface damage, and high reusability. For example, in wearable electronics, adhesives must form durable yet reversible bonds with the skin, without causing irritation or damage [11–13]. Achieving this requires a careful balance between adhesion strength, biocompatibility, and breathability to ensure comfort during extended use. Traditional adhesives, such as pressure-sensitive adhesives (PSAs) and hydrogels, have been widely adopted due to

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their ease of application and ability to dissipate mechanical energy effectively. However, these conventional materials often fall short in key areas such as reusability, biocompatibility, adhesion strength, and the programmability of adhesive properties [14–19]. These limitations restrict their effectiveness in emerging applications that demand more versatile adhesive solutions.

Recent advancements in smart adhesive technologies have focused on incorporating mechanically engineered designs—such as kirigami patterns, metastructures, and other tunable architectures—to overcome these challenges [20–31]. Unlike traditional adhesives, which primarily rely on chemical mechanisms to enhance bonding strength, mechanically structured adhesives offer a material-independent solution for achieving a wide range of adhesive properties [32–36]. By integrating spatially programmed structures, varying stiffness, or periodic configurations into adhesive materials, these designs enable enhanced adhesion properties, including stronger adhesion, repeatability, directionality, adaptability, and even programmability [37–42]. This versatility makes them particularly well-suited for emerging applications that require tailored adhesive performance.

This review explores the principles behind mechanically structured smart adhesives, with a focus on how engineered designs enhance both mechanical and adhesive properties. We begin by examining different design strategies, including kirigami patterns, metastructures, and multilayered configurations, to achieve advanced adhesive capabilities. We also discuss the underlying mechanisms by which these designs improve both mechanical performance and adhesion. Finally, we highlight the emerging applications of these advanced adhesives in biomedical devices, wearable electronics, human–machine interfaces (HMIs), and soft robotics.

2 Recent Advancement of Mechanically Structured Smart Adhesives

Engineered mechanical structures and designs offer a direct, efficient method for controlling both the adhesion and mechanical properties of adhesive films, without altering the inherent chemical or surface characteristics of the materials themselves. One of the most widely adopted approaches for integrating mechanical structures is the introduction of patterned cuts, known as kirigami, into adhesive films. This kirigami approach significantly enhances the flexibility and stretchability of the adhesive, surpassing the material's natural mechanical properties by utilizing controlled cuts [43–46]. Additionally, kirigami structures improve adhesion strength by promoting enhanced deformability and facilitating interfacial crack control [47, 48]. Other

mechanical design strategies involve arranging materials with varying mechanical rigidities in either vertical or horizontal orientations. These configurations improve adhesive performance by increasing the interfacial contact area with softer components, while simultaneously enhancing adhesion strength with stiffer materials [49, 50]. When combined with responsive materials, these mechanical structures can be dynamically modulated on demand, offering greater versatility for advanced applications [51, 52]. This section highlights recent progress in the development of advanced adhesives based on these unique mechanical structures and designs, showcasing their potential for more sophisticated and dynamic adhesive solutions.

2.1 Kirigami-Patterned Adhesives

Kirigami cut patterns have emerged as a highly promising approach in adhesive design, significantly enhancing deformability, conformability, and adhesion capacity. These engineered patterns improve the flexibility of adhesive films, allowing them to better adapt to complex, curved, and dynamically deforming surfaces, such as human skin. By strategically removing material, kirigami designs not only increase deformability but also enable more effective conformal adaptation to substrates and surfaces. This ensures intimate contact over irregular geometries, which is critical for maximizing adhesion [53–55]. Moreover, the introduction of kirigami structures can delay or control crack propagation within the adhesive layer. By distributing stress more evenly and preventing localized failure points, these patterns help maintain adhesion strength over time [56, 57]. This structural optimization contrasts with traditional methods that often compromise mechanical durability or adhesion by reducing stiffness or thickness [58, 59]. Instead, kirigami patterns leverage advanced structural engineering to enhance both adhesion performance and the overall robustness of the adhesive system [60–62].

Various cut geometries, including linear slits, Y-shaped motifs, and hierarchical patterns, can be employed to optimize key properties such as stretchability, out-of-plane deformation, and conformability in adhesive systems. These diverse kirigami-inspired designs enable fine-tuning of mechanical and adhesive responses, making them highly versatile for a range of applications. In particular, kirigami adhesives demonstrate remarkable potential in the biomedical field. Their enhanced conformability allows for the creation of bioelectronic interfaces that can form intimate contact with biological tissues, enabling long-term, high-fidelity biopotential recordings [63, 64]. The increased stretchability and adaptability of these adhesives also make them ideal candidates for wearable sensors that must endure continuous movement without compromising adhesion or functionality [65, 66].

For example, Yu et al. introduced a novel approach to developing tough hydrogel adhesives with kirigami cut patterns for compliant soft electronics (Fig. 1a) [67]. The kirigami cuts were incorporated into the films using photolithographic polymerization, significantly enhancing their stretchability and enabling better conformity to complex geometries. These hydrogel adhesives were successfully integrated with liquid metal to create flexible, motion-sensing devices, demonstrating their potential as substrates for soft electronics. Similarly, Pradhan et al. developed flexible silk kirigami adhesives with precisely defined microscale cuts that exhibited engineered elastic behavior (Fig. 1b) [68]. Through experiments and finite element analysis (FEA) simulations, they confirmed that these microscale cuts dramatically increased the flexibility and stretchability of the adhesive patches. This enhanced flexibility allowed for stable

adhesion even on highly dynamic surfaces like finger joints. Additionally, by incorporating conductive polymers, they created flexible, intrinsically electroactive kirigami adhesives suitable for bioelectronic applications.

Morikawa et al. fabricated ultrastretchable kirigami bioprobes using biocompatible parylene films embedded with metal electrodes (Fig. 1c) [44]. Their design achieved an impressive 250% strain at just 9 mN of force while maintaining a low Young's modulus of 23 kPa. These bioprobes demonstrated their utility in vivo by recording electrocorticogram signals from mouse brains and conformally wrapping around a beating mouse heart to capture epicardial signals. This showcases their ability to interface seamlessly with dynamically deforming organs. In another example, Jiang et al. introduced a snakeskin-inspired soft-hinge kirigami metamaterial adhesive (Fig. 1d), which exhibited auxetic behavior characterized by a

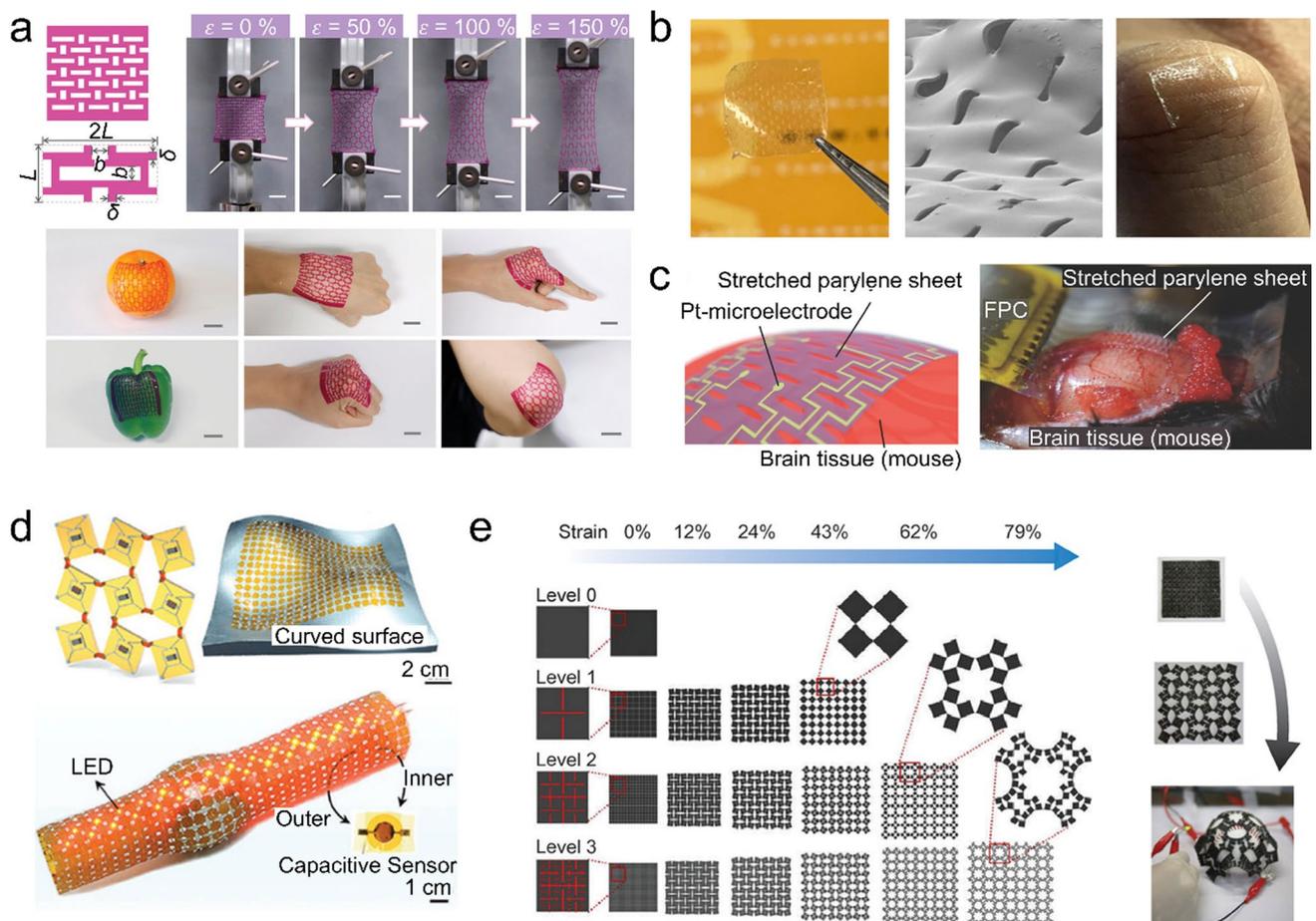


Fig. 1 Kirigami-patterned adhesives. **a** Kirigami cut-patterned hydrogel adhesives exhibiting significantly enhanced stretchability and conformability (Adapted from Ref. 58 with permission, Copyright 2021, Wiley-VCH). **b** Silk-based kirigami adhesives with microscale cuts, improving flexibility and adhesion on complex substrates (Adapted from Ref. 59 with permission, Copyright 2020, American Chemical Society). **c** Ultrastretchable kirigami in vivo bioprobes designed

for seamless integration with biological tissues (Adapted from Ref. 35 with permission, Copyright 2017, Wiley-VCH). **d** Snakeskin-inspired soft-hinge kirigami metamaterial adhesives (Adapted from Ref. 60 with permission, Copyright 2022, Wiley-VCH). **e** Fractal-cut patterned kirigami adhesives (Adapted from Ref. 61 with permission, Copyright 2014, National Academy of Sciences)

negative Poisson's ratio [69]. This design allowed for significant biaxial stretching and featured soft hinges that absorbed and dissipated loads during deformation, effectively preventing buckling and delamination. The result was a smooth and conformal surface adaptation on intricate 3D geometries, enhancing both the mechanical performance and versatility of the adhesive. Lastly, Cho et al. explored fractal cut patterns that yielded highly adaptable macroscopic structures (Fig. 1e) [70]. Their hierarchical fractal cut design divided materials into interconnected rotating units that expanded surface area when stretched without deforming the units themselves. This approach resulted in robust materials capable of enduring extensive mechanical deformation with minimal internal strain, broadening their potential applications in flexible and stretchable technologies. These examples highlight how kirigami-inspired designs can be tailored to meet specific functional requirements across various fields, particularly where flexibility, stretchability, and conformal adhesion are critical factors.

2.2 Nonlinear Kirigami-Patterned Adhesives

Kirigami cut patterns, which typically consist of linear slits or simple geometric motifs, have been widely used to enhance the flexibility, stretchability, and conformability of materials. However, these traditional patterns often lack the ability to significantly control adhesion strength or crack propagation. In contrast, nonlinear cut patterns introduce more complex geometries that offer additional functionalities beyond those of linear cuts. These nonlinear designs enable more precise control over mechanical responses, particularly in managing crack propagation and adhesion performance [71]. Unlike linear cuts, which primarily enhance deformability, nonlinear cuts can dramatically improve adhesion by manipulating the direction and behavior of crack growth, making them a powerful tool for creating adhesives with tunable and reversible properties [72, 73].

Nonlinear cuts have gained attention as a novel method to dramatically enhance adhesion strength through a simple yet effective approach. The presence of these nonlinear cuts allows adhesives to arrest and reverse crack propagation at the interconnects, thereby delaying overall crack growth. This reverse crack propagation transforms a high global peel angle into a lower local peel angle, which significantly improves adhesion performance. According to the Kendall peel model, the peel angle plays a critical role in determining the peeling behavior of a non-extensible adhesive, described by: [74, 75]

$$\frac{F_c}{w} = \frac{G_c}{1 - \cos\theta}$$

where F_c is the peel force at an angle θ from the substrate, w represents the film width, and G_c is the adhesion energy. This

equation highlights that adhesion strength is directly proportional to adhesion energy and inversely proportional to the peeling angle. By lowering the local peel angle through nonlinear cut patterns, the adhesive can achieve higher adhesion strength while maintaining flexibility. Moreover, these nonlinear patterns allow for controlled crack propagation based on the direction of peeling, enabling their use as reversible adhesives. This anisotropic behavior—where adhesion strength varies depending on the peeling direction—enables programmable adhesion for adhesive patches that can be tailored for specific applications requiring both strong bonding and easy release.

Hwang et al. employed an innovative adhesive design based on metamaterials that utilize programmed nonlinear cut patterns to achieve both powerful bonding and easy release capabilities (Fig. 2a) [73]. These nonlinear cuts uniquely suppress crack propagation by forcing cracks to propagate backwards at interconnects, resulting in up to a 60× enhancement in adhesion strength compared to unpatterned adhesives. Simultaneously, they allow easier crack propagation in the reverse peel direction for simple detachment and reuse, demonstrating up to a 25× difference between maximum and minimum adhesion directions. The versatility of this design was demonstrated across various adhesive materials, substrates, and environmental conditions. Furthermore, practical applications such as box tape and adhesive gloves were explored, suggesting that nonlinear kirigami-patterned adhesives can be widely used in fields requiring both strong adhesion and switchable characteristics. This foundational work laid the groundwork for using nonlinear cuts to control crack propagation in adhesives, introducing key concepts that subsequent research has built upon. Li et al. provided a deeper theoretical understanding of nonlinear cut adhesives with high directional asymmetry [71]. Their model explained how adhesive stiffness plays a crucial role in enhancing directional adhesion and how nonlinear cut patterns dissipate in-plane elastic energy to further strengthen adhesion.

Park et al. advanced this concept by introducing a hybrid adhesive system that combines microscale adhesive pillar arrays with macroscopic nonlinear cut architectures (Fig. 2b, c) [76]. This multiscale design synergistically enhances pull-off adhesion, peel adhesion, and directional control of adhesion strength. The microscale pillars work in conjunction with the nonlinear cuts to enable crack trapping and reversion across multiple length scales, resulting in significantly enhanced adhesion capacity compared to any other control adhesive samples—including planar adhesives, nonlinear cut adhesives alone, or even commercial adhesives. Furthermore, the micropillars provide enhanced adaptability to rough surfaces. As a result, this hybrid adhesive demonstrated exceptional performance on rough and irregular surfaces such as human skin, achieving

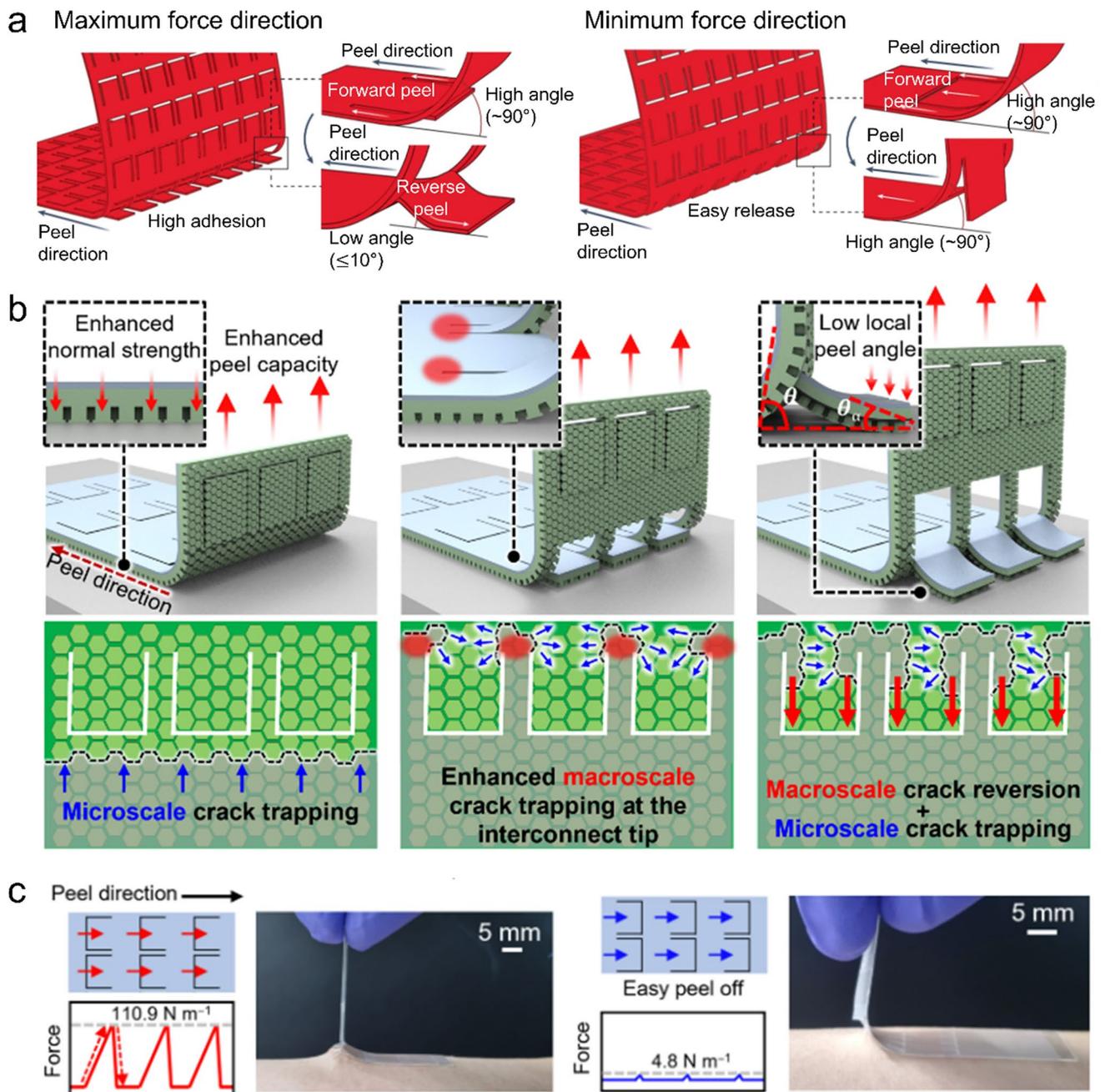


Fig. 2 Nonlinear kirigami-patterned adhesives. **a** Schematic of meta-material adhesives featuring nonlinear cut patterns (Adapted from Ref. 63 with permission, Copyright 2024, Springer Nature). **b** Illustration of a hybrid adhesive integrating microscale pillar arrays with

macroscale nonlinear cuts. **c** Example of the hybrid adhesive exhibiting directional adhesion on human skin. **b**, **c** Adapted from Ref. 67 with permission, Copyright 2023, The American Association for the Advancement of Science

up to a 58.4-fold improvement in adhesion strength compared to flat adhesives. This remarkable enhancement is attributed to the microscale structures forming a high contact area on uneven surfaces, ensuring better surface conformity and stronger bonding. Park et al. further showcased the practical applications of this technology by developing programmable skin adhesive patches with

independently tunable adhesion strength and directionality at specific locations. These patches hold significant potential for use in wearable electronics—particularly in applications such as motion detection and virtual reality control—where both strong adhesion and adaptability to dynamic movements are essential.

2.3 Adhesives based on Horizontally Varying Rigidity

Adhesives with spatial variations in rigidity across the horizontal 2D plane have emerged as innovative designs that simultaneously enhance both mechanical and adhesive performance. These designs, often referred to as tessellated patterns, involve engineering periodic changes in material properties, such as elastic moduli or film thickness, across the adhesive surface [77]. By introducing these variations in material stiffness, these adhesives exhibit improved mechanical strength, toughness, and superior resistance to fracture and fatigue [78, 79].

Recent studies have shown that tessellated patterns not only enhance the mechanical properties of adhesive films but also significantly influence their adhesive performance. Most notably, these patterns offer powerful mechanisms for improving peeling resistance [80]. In adhesive systems with regions of differing bending stiffness, crack propagation during peeling can be arrested or significantly delayed at interfaces between areas with contrasting stiffness. As a result, adhesives engineered with spatial variations in stiffness demonstrate enhanced interfacial toughness compared to uniform systems. This enhancement in peeling force can be understood through Griffith's energy balance approach to fracture mechanics, where the driving force for peeling is given by [75]:

$$G = \frac{1}{b} \frac{d(W - U)}{dc}$$

where W is the work done by external forces, U is the stored elastic energy, b is the width of the adhesive film, and c is the crack length. In systems with varying stiffness, rapid fluctuations in stored elastic energy (U) alter how efficiently external work (W) is converted into crack-driving force. This results in a spatially varying effective adhesion energy that can be much higher than the intrinsic interface strength. As the peeling front moves from a compliant region to a stiffer one, it encounters increased resistance because the stiffer material resists deformation more effectively. A significant portion of the work done by the peel force is absorbed into bending the stiffer region, leaving less energy available to drive crack growth—thus retarding or arresting crack propagation [81–83].

The magnitude of this effect depends on the ratio of bending stiffness between adjacent regions. For a crack approaching an interface between materials with different bending stiffnesses, the enhancement in peeling force can be expressed as [77]:

$$\frac{F}{b} = \frac{E_2 I_2}{E_1 I_1} R$$

where $E_1 I_1$ and $E_2 I_2$ are the bending stiffness of materials 1 and 2, respectively, and R is the intrinsic fracture energy of the interface. This increase in peeling force occurs due to changes in bending behavior at the interface between regions with different stiffnesses. By strategically introducing periodic variations in mechanical properties, adhesion forces can be dramatically improved without altering the adhesive material itself.

For example, Xia et al. investigated how variations in stiffness across adhesive systems affect asymmetry in peeling behavior (Fig. 3a) [80]. They demonstrated that patterning elastic bending stiffness across adhesive films creates periodic fluctuations in adhesion force during peeling, resulting in significantly enhanced peel adhesion strength. By incorporating periodic variations in material properties or structural features into adhesives, researchers have developed systems with substantially higher adhesion strength compared to uniform counterparts. Xu et al. further explored this concept by proposing a cohesive zone fracture model to analyze peeling behavior during debonding of films with varying stiffness [81]. Their model examined instability during debonding and provided insights into how this instability could be leveraged to design adhesives with enhanced fracture toughness and reliability—without requiring modifications to the interfacing material itself. Meanwhile, Hwang et al. explored approaches to control and enhance adhesion through engineered variations in material properties (Fig. 3b, c) [84]. One promising strategy involved creating alternating stiff and compliant regions through strategic cuts in materials. This design allowed researchers to spatially control adhesion strength by tuning bending rigidity and contact width across patterned adhesive sheets. Their approach demonstrated up to a 100-fold improvement in adhesion strength compared to uniform systems.

Another innovative approach involves incorporating active materials into tessellated designs to dynamically control peeling behavior. For instance, Choi et al. developed a hybrid tessellated skin patch for wearable electronics, which integrates shape memory polymers (SMPs) arranged in a tessellated array (Fig. 3d–g) [11]. The SMPs can modulate their stiffness on demand through thermal control, allowing the patch to adapt to various conditions. This design not only enhances deformability but also provides strong, repeatable adhesion on dynamically deforming surfaces like human skin. At elevated temperatures, the SMPs soften, allowing the patch to conform closely to the skin's surface. Upon cooling, the SMPs stiffen, locking the patch in place and significantly increasing adhesion strength. This on-demand switchable adhesion enables easy detachment without damaging the skin or adhesive. This feature is particularly useful for wearable electronics that need to maintain consistent performance while accommodating body motions.

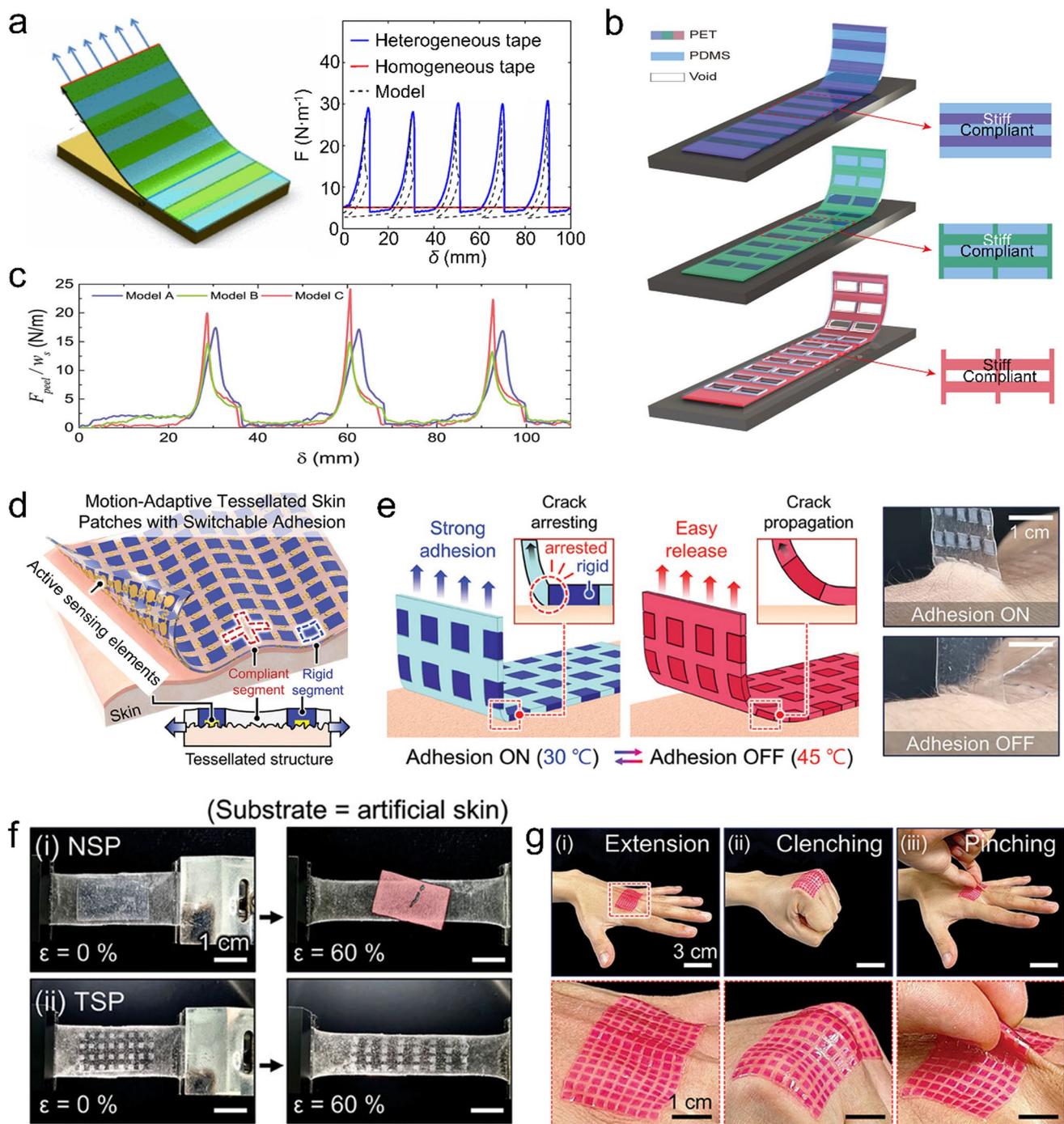


Fig. 3 Adhesives based on horizontally varying rigidity. **a** Adhesive structures exhibiting enhanced adhesion through variations in bending stiffness (Adapted from Ref. 71 with permission, Copyright 2012, American Physical Society). **b** Different adhesive patterns featuring alternating stiff and compliant regions for controlled adhesion performance. **c** Peeling force curves of various adhesive models, highlighting periodic crack arresting behavior. **b, c** Adapted from Ref. 75 with permission, Copyright 2018, American Chemical Soci-

ety. **d** Motion-adaptive tessellated skin patch (TSP) with compliant and rigid SMP segments. **e** Tunable adhesive properties of the TSP, demonstrating crack arresting at lower temperatures (30 °C) and easy release at higher temperatures (45 °C). **f** Adhesion retention of the TSP under 60% uniaxial tensile strain. **g** Strong adhesion of the TSP during dynamic hand motions. **d, g** Adapted from Ref. 8 with permission, Copyright 2024, Wiley-VCH

Additionally, Haverkamp et al. explored integrating active granular jamming layers into adhesive films as another method for controlling rigidity and peeling behavior [85]. The particulate materials within these jamming layers can reversibly lock together under negative pressure, increasing the bending stiffness of the adhesive system by up to 11 times, effectively arresting crack propagation. Releasing the pressure softens the interface and facilitates crack propagation when needed. This highly reversible mechanism allows for precise control over adhesive behavior at specific locations and directions. These advancements open new avenues for designing high-performance adhesives with tailored mechanical properties and tunable peeling behavior through spatial variation in material properties.

2.4 Adhesives based on Vertically Varying Rigidity

Adhesives with multilayer structures featuring varying rigidity across their vertical planes have been developed to enhance both surface adaptability and adhesion strength. This multilayered approach allows for the optimization of different mechanical properties within a single adhesive system, combining the benefits of soft and rigid layers. The soft layer significantly increases the actual contact area under the same preload, improving surface conformability by allowing the adhesive to better adapt to rough or uneven surfaces [86, 87]. However, soft layers alone may suffer from easy detachment at stress concentration points along the adhesive interface. To address this, a rigid layer is incorporated to distribute stress more evenly and prevent localized peeling, promoting more uniform separation from the target surface [86]. This combination of soft and rigid layers not only enhances surface conformability but also substantially improves adhesion strength by balancing flexibility with mechanical stability. For instance, Tian et al. developed a core–shell bilayer dry adhesive optimized for rough surfaces (Fig. 4a) [86]. Their design features a mushroom-shaped structure with a rigid core and soft shell, which provides excellent adhesion across surfaces with roughness ranging from nanoscale to microscale. The soft shell increases the contact area, while the rigid core prevents premature detachment at high-stress regions, addressing a common limitation of purely soft adhesives. This structure also enhances peeling resistance by distributing stress more effectively.

Furthermore, introducing stimulus-responsive layers can further improve performance. For example, Wang et al. created a stiffness-tunable smart adhesive that mimics muscle tissue and sensing nerves (Fig. 4b) [87]. This design incorporates a conductive network filled with magnetorheological grease beneath an adhesive structural layer. Without a magnetic field, the magneto-responsive layer remains soft, adapting easily to various surfaces. When exposed to a magnetic field, the layer stiffens, locking its shape and

enhancing adhesion strength. This bilayer structure enables rapid attachment and detachment while maintaining strong surface conformity. Similarly, Heo et al. designed a multilayered artificial skin material inspired by the human palm to improve robotic hand manipulation capabilities (Fig. 4c) [88]. The artificial skin combines a porous latex outer layer with a rigid silicone inner layer. The soft outer layer adapts to the shape of objects, maximizing contact area, while the rigid inner layer provides stability and force transmission during manipulation. This multilayer approach significantly enhances the ability of robotic hands to grasp and manipulate objects of various shapes and sizes more effectively than conventional designs. These examples demonstrate that multilayer adhesives with vertically varying rigidity offer significant advantages in terms of both adaptability and strength. By strategically combining soft and rigid layers, these adhesives can achieve enhanced performance across a wide range of applications, from wearable electronics to robotics.

3 Applications of Mechanically Structured Smart Adhesives

Mechanically structured smart adhesives offer a range of programmable properties, including tunable adhesion strength, directionality, mechanical deformability, surface conformability, and on-demand switchable adhesion. These features make them highly adaptable to dynamic and complex substrates, such as human skin, where stable interfacing is required under challenging conditions [43, 89–92]. As a result, these adhesives are increasingly used in cutting-edge applications like wearable healthcare devices, human–machine interfaces, biomedical devices, and soft robotics.

For example, Choi et al. developed a wearable healthcare device using a motion-adaptive tessellated skin patch composed of rigid and compliant shape memory polymers (SMPs) (Fig. 5a) [11]. This device is capable of monitoring multiple physiological signals simultaneously, including three-axis acceleration, ECG, PPG, blood pressure, and heart rate. The tessellated patch demonstrates strong skin adhesion due to its SMP-based mechanism, which allows for easy detachment when heated. Despite integrating bulky electronic components, the patch maintains stable attachment to the skin while conforming to body movements during activities like running or jumping. The physiological data collected shows clear distinctions between different activity states, highlighting the device's potential for continuous health monitoring.

Yamagishi et al. introduced an elastic kirigami patch designed for electromyographic (EMG) analysis during sports activities (Fig. 5b) [93]. The patch features conductive nanosheets integrated with elastic kirigami cut patterns that conform to the complex curvature of the palm.

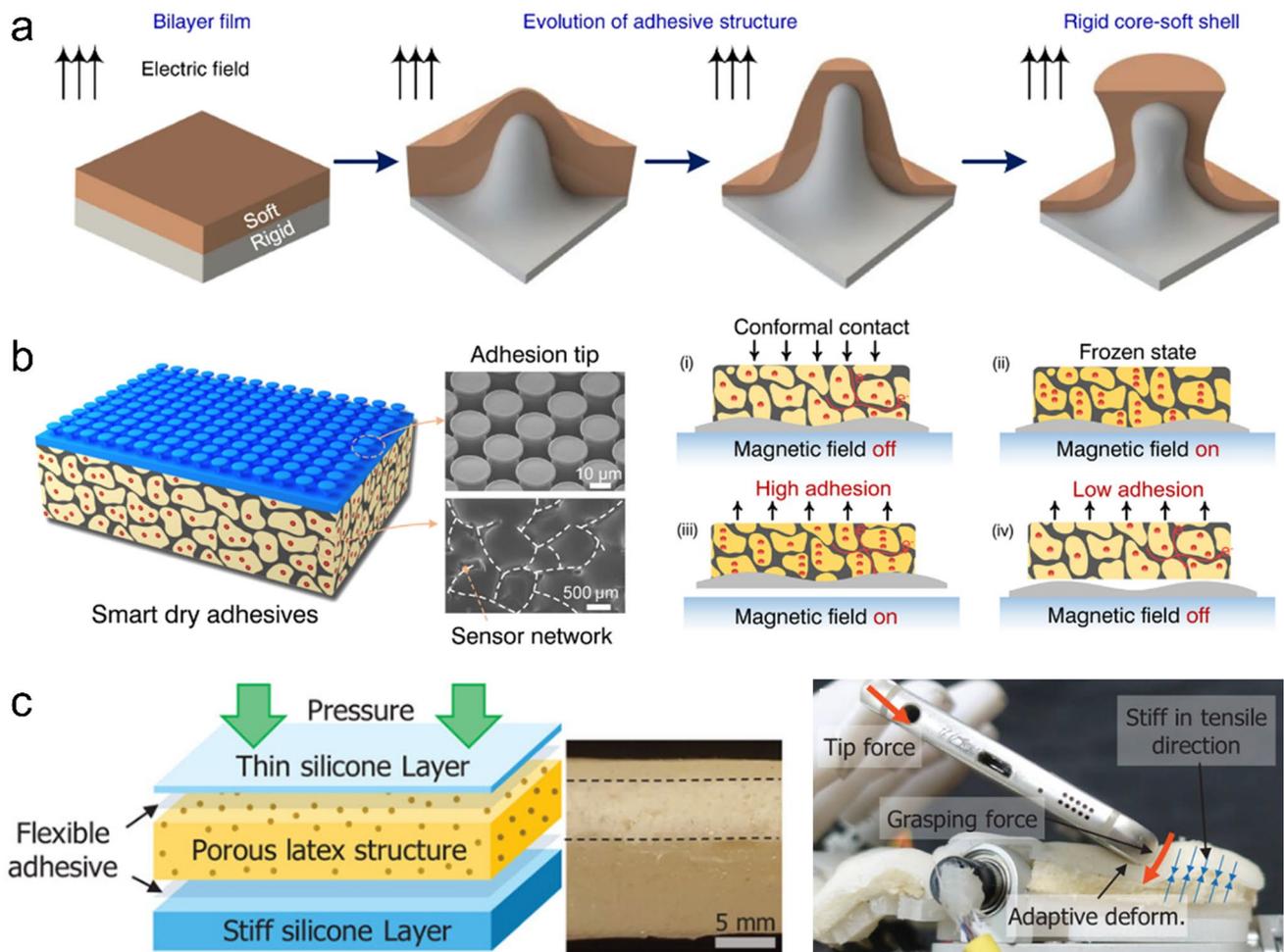


Fig. 4 Adhesives based on vertically varying rigidity. **a** Schematic of a core-shell bilayer dry adhesive with a rigid core and soft shell (Adapted from Ref. 77 with permission, Copyright 2022, Springer Nature). **b** Design of a stiffness-tunable smart adhesive incorporating a magneto-responsive layer (Adapted from Ref. 78 with permission,

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This design ensures stable contact during intense movements while providing accurate EMG measurements. It has proven particularly effective in analyzing muscle activity during baseball pitching, demonstrating its potential for sports performance monitoring and injury prevention. In another example, Morikawa et al. developed a kirigami-based neural interface optimized for adaptability to biological tissues (Fig. 5c) [94]. The kirigami structure allows for optimal conformability to nerve tissues while maintaining mechanical stability during movement. In experimental studies, the device successfully recorded EMG signals across various stimulation intensities, with clear differentiation between stimulation artifacts and actual EMG responses. This interface holds significant potential for advanced neuromodulation applications and neural interface development.

Expanding on these innovations, Choi et al. also introduced a wrist-mounted electronic heating device that leverages a stretchable kirigami design for precise temperature control (Fig. 6a) [95]. The system provides uniform heat distribution across the wrist by forming conformal contact with the skin through its sophisticated kirigami structure. Thermal imaging validated its effectiveness in maintaining consistent temperatures between 23.5 and 37.0 °C. In virtual reality technology, Park et al. created a heterogeneous skin patch featuring microstructured adhesives and nonlinear cut patterns (Fig. 6b) [76]. Integrated with electronic components such as Bluetooth modules and gyroscope sensors, this patch provides precise motion tracking for translating hand movements into virtual avatar controls.

Meanwhile, Heo et al. designed a robotic hand manipulator based on a multilayered adhesive system comprising silicone layers and porous latex structures (Fig. 6c) [88].

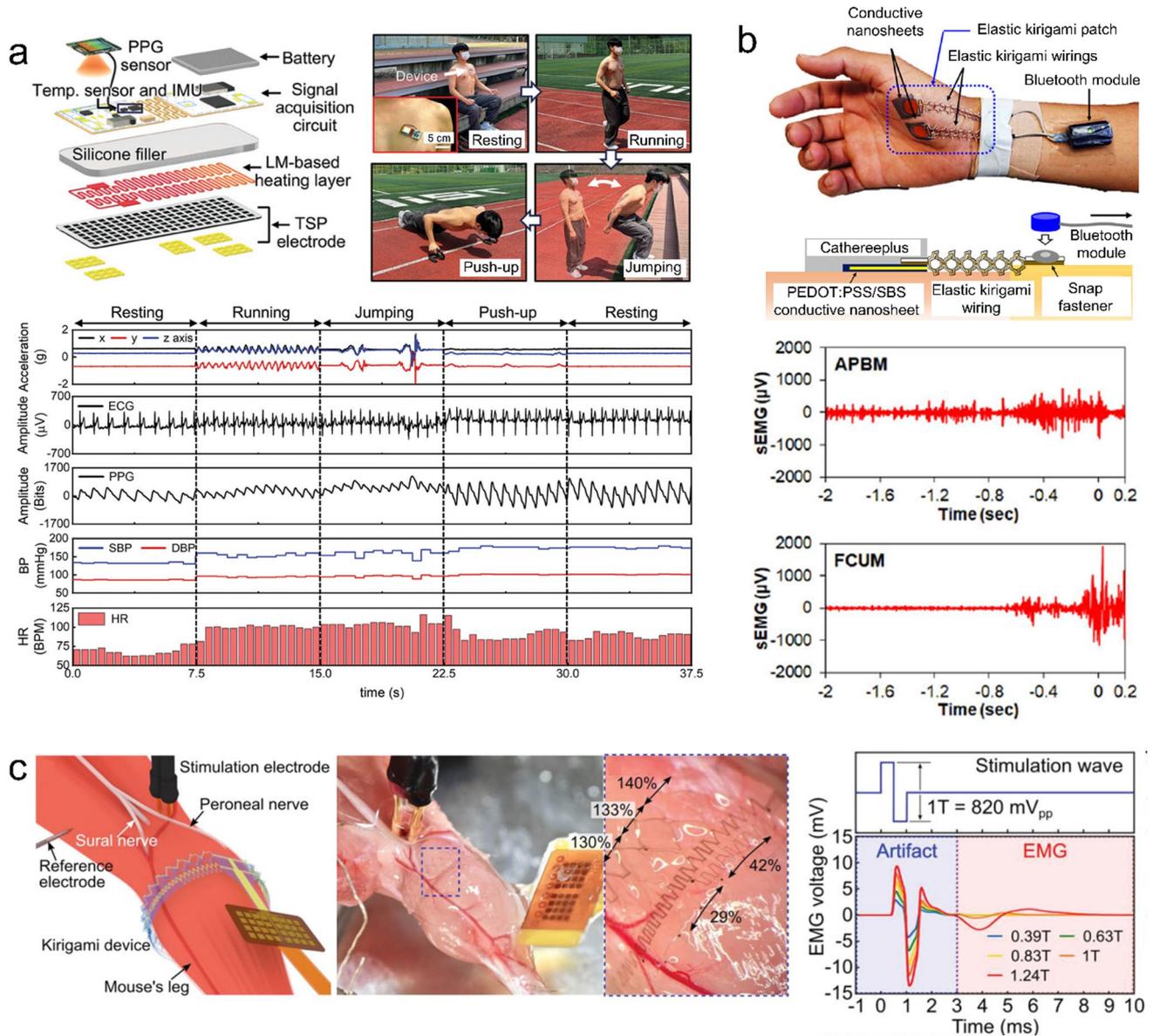


Fig. 5 Applications of mechanically structured smart adhesives in wearable healthcare devices. **a** Healthcare monitoring device utilizing motion-adaptive tessellated skin patches (Adapted from Ref. 8 with permission, Copyright 2024, Wiley-VCH). **b** sEMG recording enabled by an elastic kirigami patch (Adapted from Ref. 84 with per-

mission, Copyright 2019, Springer Nature). **c** In vivo EMG signal recording from a mouse's hind limb using a donut-shaped stretchable kirigami patch (Adapted from Ref. 85 with permission, Copyright 2019, Wiley-VCH)

This design allows the manipulator to adapt to various surface conditions while maintaining structural integrity. It has been successfully applied to surfaces with multiple creases and curvatures, making it ideal for challenging manipulation tasks in robotics. Lastly, Wang et al. developed a smart gripper using multilayered stiffness-tunable adhesives that combine soft bioinspired layers with magneto-responsive materials (Fig. 6d) [87]. This system achieves high surface conformability with various objects and allows easy detachment in response to magnetic fields. Its versatility was

demonstrated by successfully gripping objects of different shapes and sizes, showcasing its potential in adaptive robotic systems.

4 Conclusion

Mechanically structured smart adhesives mark a significant leap beyond traditional adhesive systems, offering superior adhesion strength, flexibility, and adaptability. By

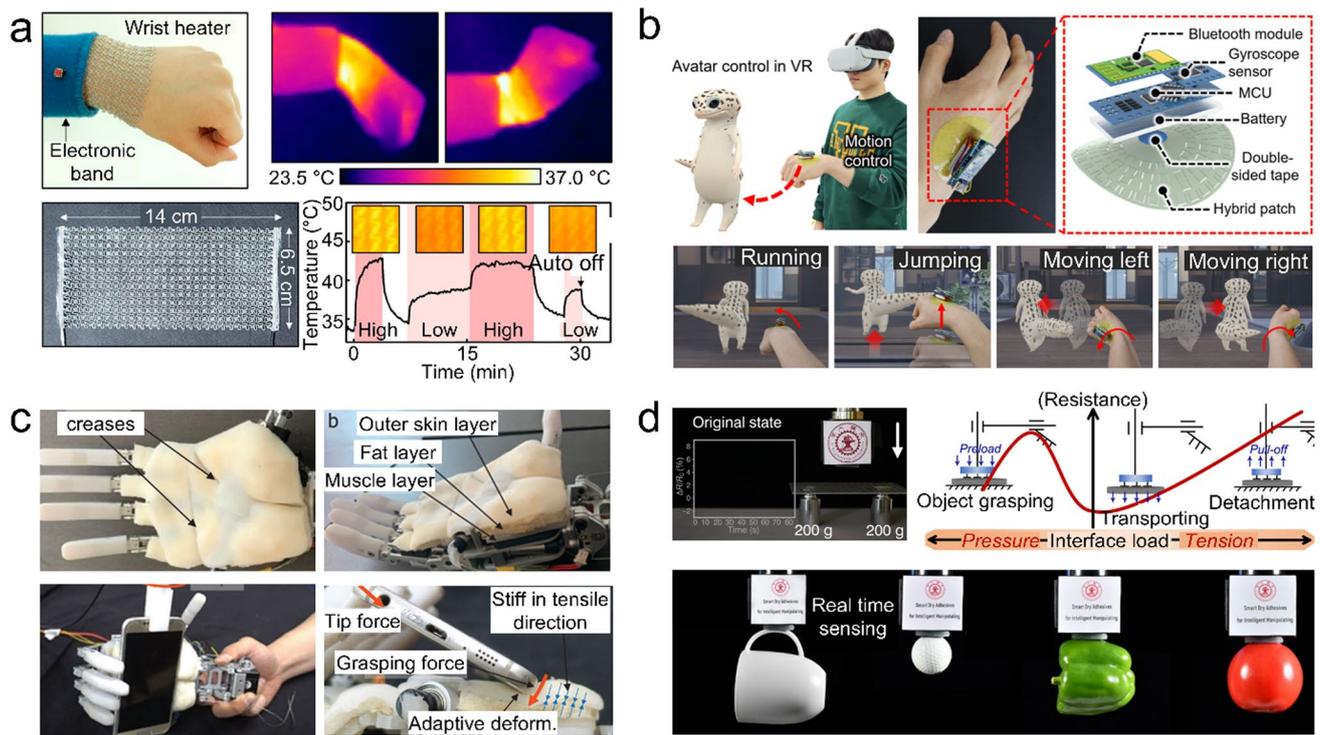


Fig. 6 Applications of mechanically structured smart adhesives in wearable electronics and robotics. **a** Mesh-structured stretchable thermal device applied to the human wrist during dynamic motion, demonstrating its use in wearable thermotherapy (Adapted from Ref. 86 with permission, Copyright 2015, American Chemical Society). **b** Adhesive patch with integrated devices and nonlinear kirigami patterns, adhered to the human hand for VR applications (Adapted from Ref. 67 with permission, Copyright 2023, The American Association

for the Advancement of Science). **c** Prosthetic hand with a multilayered structure grasping a smartphone, showcasing its potential for gripper applications (Adapted from Ref. 79 with permission, Copyright 2020, Wiley-VCH). **d** Robotic manipulation system using an active material-based multilayered adhesive for picking and placing various objects (Adapted from Ref. 78 with permission, Copyright 2023, The American Association for the Advancement of Science)

incorporating advanced mechanical designs such as kirigami patterns, tessellations, and multilayer configurations, these adhesives achieve enhanced mechanical and surface properties without the need for chemical alterations. This review has demonstrated how these engineered structures elevate adhesive performance across a wide range of applications, particularly in wearable healthcare devices, flexible electronics, biomedical devices, and soft robotics.

Among these innovations, mechanically structured adhesives with kirigami-inspired designs exhibit exceptional stretchability and conformability, making intimate contact with complex surfaces like human skin. These attributes are essential for applications requiring both durable adhesion and comfort, especially in dynamic environments. Furthermore, nonlinear kirigami patterns and tessellated designs offer programmable, reversible adhesion, making them ideal for advanced applications where tunable and directional adhesion are necessary. In addition, multilayered adhesives with vertically varying rigidity have proven effective in optimizing both adhesion strength and surface adaptability. By combining soft, conformable outer layers with rigid inner

structures, these adhesives balance flexibility and mechanical stability, making them suitable for tasks that demand high performance and adaptability. Looking forward, the future of smart adhesives lies in the exploration of responsive materials like shape memory polymers (SMPs) and magneto-responsive layers, which can dynamically adjust adhesion properties. These technologies will enable the creation of next-generation adhesives capable of on-demand switchable adhesion and improved reusability.

Despite these recent advancements, several challenges remain. The incorporation of complex mechanical structures, such as microstructures and multilayer configurations, often requires more sophisticated and labor-intensive fabrication processes, which may hinder scalability, especially for large-area applications. Additionally, developing manufacturing techniques that can consistently and economically produce these intricate structures on an industrial scale is crucial. Many of these adhesives also face limitations in long-term durability and reliability under harsh conditions, such as wet, rough, or extreme temperature surfaces, which must be addressed to fully realize their potential in real-world

applications. Nevertheless, as research in this field continues to advance, we anticipate that mechanically engineered smart adhesives, combined with innovative material designs, will revolutionize industries such as wearables, robotics, and manufacturing.

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Declarations

Conflict of interests The authors declare that they have no competing interests.

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