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Research Article

EPIDERMAL HAPTIC INTERFACES: PHYSIOLOGICAL FOUNDATIONS, ACTUATION TECHNOLOGIES, AND BIOCOMPATIBLE MATERIALS

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Abstract

Epidermal haptic interfaces that laminate directly onto the skin have drawn attention as a promising strategy to overcome the limitations of rigid, irritative haptic hardware in current virtual and augmented reality (VR/AR) systems and broader bioelectronic applications. This article reviews the physiological foundations, actuation technologies, and material strategies that underpin these next-generation skin-integrated systems, with a focus on achieving mechanical and sensory compatibility with human tissue. First, the anatomy of the skin and the functional roles of four primary mechanoreceptors are summarized to understand the fundamentals of sensations, which will be basis for designing parameters of the system such as optimal vibration frequency ranges, spatial resolution, and actuator placement informed by regional variations in touch sensitivity and two-point discrimination thresholds. Next, major haptic actuation modalities including electromagnetic, pneumatic/hydraulic, shape memory alloy, electrostatic (dielectric elastomer), thermal, and electrical (TENS and electrotactile) approaches are compared in terms of bandwidth, force output, form factor, and suitability for soft, wearable vibrohaptic systems. Then we will review the soft substrates conductive elements, and encapsulation strategies that enable mechanical matching to skin, stable electrical performance under large strain, and long-term skin contact. Finally, the article outlines remaining challenges including robust adhesion, high-density actuation, power and wireless communication, durability, and user comfort and highlights future directions such as self-healing and two-dimensional materials, AI-driven personalized haptics, multimodal sensory integration, and system-on-patch architectures for applications in VR/AR, prosthetics, human–robot interaction, telemedicine, and continuous health monitoring.

Keywords: Epidermal haptic, Technologies.

INTRODUCTION

The Evolution of Haptic Interfaces: From Rigid Systems to Skin-Integrated Electronics

The sensation through the skin is fundamental to human interaction with the external world, providing the ability to perceive texture, pressure, temperature, and vibration through sophisticated mechanoreceptors distributed across our skin [1,2]. While visual and auditory information can now be transmitted vividly through high-resolution displays and spatial audio systems, haptic feedback has remained a significant challenge in human-machine interfaces. Traditional haptic systems, such as vibrating motors in smartphones or mechanical feedback joysticks, rely on bulky and rigid components that limit intimate interaction with the human body [3,4].To bridge this gap, the past decade has seen a paradigm shift toward soft, skin-conformal haptic interfaces capable of forming intimate connections directly on the epidermis. These epidermal haptic systems leverage advances in materials science, soft electronics, and soft robotics to create devices that mechanically match the properties of human skin [5,6]. By achieving thickness profiles of less than 100 micrometers and a Young's modulus comparable to skin tissue (~60 kPa to 1 MPa), these interfaces become nearly imperceptible to the user while maintaining stable contact even during motion [7,8]. This minimization of mechanical mismatch not only enhances wearing comfort but also preserves the spatial fidelity of tactile stimulation under dynamic deformation.

Despite these advancements in soft materials, most contemporary Virtual and Augmented Reality (VR/AR) systems still struggle to achieve true immersion, relying primarily on visual and auditory cues. While head-mounted displays create realistic virtual environments, the sense of physical presence remains limited when users cannot meaningfully "touch" virtual objects. Conventional rigid haptic hardware such as handheld controllers and force-feedback devices often limits natural movement and reduces long-term wear ability due to bulky structures and wired connections. Consequently, existing systems fail to deliver proper interactions across the full body area, underscoring an urgent need for haptic approaches that move beyond rigid, device-centered designs.

In previous work, *"Skin-Integrated Vibrohaptic Interfaces for Virtual and Augmented Reality,"* Jung et al. examine how skin-integrated vibro-haptic technology specifically addresses this lack of realistic touch[9]. The authors demonstrate that these systems, which use controlled mechanical vibrations to stimulate the skin, offer a highly effective method for producing immersive artificial sensations. Unlike current haptic gloves or vests that rely on heavy motors and external wiring, skin-integrated interfaces are thin, lightweight, and flexible. Because these epidermal electronics laminate directly onto the skin and conform naturally to its surface, they exert minimal mechanical pressure. This allows them to be applied across various body regions, enabling a full-body tactile experience rather than restricting sensations to the hands alone. However, to fully appreciate how these integrated systems reproduce such convincing sensations, it is first necessary to consider the biological mechanisms underlying human touch perception.

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Physiological Foundations of Sensation

Skin Anatomy and Mechanoreceptors

Skin as one of the largest organs in the body has multiple key features for interacting dynamically with the external environments. Basically, the function of the skin includes a barrier against environmental hazards, for examples, toxic chemicals, humidity, physical stress. It consists of several layers, each with specific functions: the epidermis, dermis, and hypodermis [10]. The epidermis is the outermost layer of the skin and serves as the primary protective barrier. It prevents water loss, blocks harmful substances, supports innate immune responses, and protects the body from ultraviolet (UV) radiation. Although the epidermis contains few sensory receptors, it is essential for protecting embedded sensory structures. The dermis is the thickest layer of the skin and functions as an integrated structural and biological system composed of fibrous, cellular, and acellular matrices. It contains various types of cells, including fibroblasts, macrophages, and mast cells. Importantly, most mechanoreceptors, such as Meissner's corpuscles, Merkel cell complexes, Ruffini endings, and Pacinian corpuscles, are primarily located within the dermis. These receptors enable the perception of touch, pressure, vibration, and skin stretch. In addition, the dermis includes well-developed vascular, lymphatic, and nervous networks, which are essential for nutrient supply, temperature regulation, and sensory perception.The hypodermis, also known as the subcutaneous layer, is located beneath the dermis. It provides mechanical cushioning and physiological support and contains abundant blood vessels and nerves. Some deep-pressure and vibration receptors, particularly Pacinian corpuscles, may extend into the hypodermis, contributing to deep tactile sensation. This layer is important in terms of energy storage and thermal insulation.

Four types of mechanoreceptors and perceptions

Human skin contains specialized mechanoreceptors distributed within the dermal layers that transduce mechanical deformation into neural signals. These receptors differ in receptive field size, adaptation rate, and depth within the skin, all of which influence how tactile information is encoded and perceived. Four primary types of mechanoreceptors Merkel receptors, Meissner corpuscles, Ruffini endings, and Pacinian corpuscles enable the perception of pressure, texture, motion, skin stretch, and vibration, respectively (Figure 1) [11]. Merkel receptors are slowly adapting receptors with small receptive fields, making them essential for detecting sustained pressure and fine spatial details such as edges and shapes. Meissner corpuscles, which adapt more rapidly, respond to low-frequency vibrations and dynamic skin deformation, contributing to the perception of motion and slip across the skin. Ruffini endings are sensitive to skin stretch and provide information relevant to finger position and object manipulation. Pacinian corpuscles, located deeper in the skin, are rapidly adapting receptors with large receptive fields and are particularly sensitive to high-frequency vibrations. Their peak sensitivity occurs between approximately 200 and 250 Hz, allowing them to detect extremely small skin displacements. This property makes Pacinian corpuscles especially relevant for vibrohaptic interfaces, as perceptible tactile sensations can be generated with minimal mechanical amplitude.

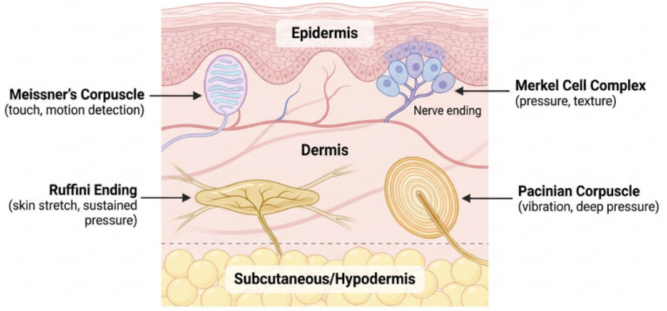

Figure 1. Four types of mechanoreceptors located within the Dermis

Touch sensitivity varies across different regions of the body due to the nonuniform distribution of mechanoreceptors. Areas such as the fingertips and face exhibit high receptor density and fine spatial resolution, whereas regions such as the back are less sensitive. This variation has important implications for vibrohaptic system design, as highly sensitive areas require finer spatial resolution and lower activation forces.In addition, tactile perception is influenced by spatiotemporal integration, in which vibrations applied at one location can propagate across neighboring regions of the skin and contribute to the perception of texture and motion. This spatial interaction further affects how tactile stimuli are perceived over larger skin areas. Closely related to this spatial sensitivity is the concept of two-point discrimination, which refers to the minimum distance at which two simultaneous tactile stimuli are perceived as distinct [12]. Regions with high mechanoreceptor density, such as the fingertips, exhibit small two-point discrimination thresholds, whereas less sensitive areas show larger thresholds. For skin-integrated vibrohaptic systems, this implies that actuator spacing must be tailored to the stimulation site in order to produce perceptually distinct and realistic tactile patterns. Failure to account for two-point discrimination limits can result in blurred or indistinguishable sensations, thereby reducing the effectiveness of haptic feedback.

Actuation Technologies and Materials

Mechanical Actuators

Mechanical actuators form the foundational methodology for generating tactile feedback in vibrohaptic systems. Among them, electromagnetic actuators such as voice coil motors (VCMs) and linear resonant actuators (LRAs) are widely adopted due to their robust performance and precise control [13]. These actuators convert electrical energy into mechanical vibrations through electromagnetic forces, enabling controlled vibration amplitude and frequency suitable for tactile feedback applications. Their relatively compact size and fast response times make them favorable for integration into wearable devices and mobile interfaces that require reliable haptic cues. Recent research has demonstrated hybrid implementations combining pneumatic and electromagnetic actuators to enhance both high-frequency and low-frequency tactile components, capitalizing on the strengths of each modality to deliver more realistic tactile feedback. This approach has shown promise in improving the fidelity of tactile signal transmission in soft wearable haptic devices. Pneumatic and hydraulic systems, in contrast, produce actuation via pressurized air or fluid. These mechanisms can generate larger mechanical forces and more complex deformation patterns than purely electromagnetic counterparts, making them particularly useful for applications involving force feedback or dynamic surface shape changes. However, their reliance on external pumps or reservoirs typically leads to increased system bulk and integration challenges, limiting their use in lightweight or highly portable systems. Shape memory alloys (SMAs) represent an alternative class of mechanical actuators activated by thermal stimuli [14]. SMAs exploit reversible phase transitions to return to a pre-defined shape after deformation, enabling contraction or expansion when heated through electrical current. This characteristic allows high force density and potentially compact actuation mechanisms. Their relatively simple structural requirements and large strain capabilities have driven interest in wearable haptics, particularly where forceful mechanical displacement is required. However, SMA actuators inherently experience slower response times and reduced operational bandwidth due to thermal cycling, posing limitations for high-frequency vibrotactile applications.

Electrostatic and Thermal Actuators

Beyond purely mechanical approaches, electrostatic and thermal actuation mechanisms provide alternative means of generating tactile sensations without large moving parts. Dielectric elastomer actuators (DEAs) are a leading example of electrostatic soft actuators that harness compliant electroactive polymer layers sandwiched between flexible electrodes [15]. When an electric field is applied, electrostatic pressure induces significant deformation in the elastomer, thereby producing mechanical actuation. DEAs are notable for their high strain capabilities, fast response times, lightweight structure, and capacity for large displacement, making them attractive for soft vibrotactile actuators and surface deformation interfaces. Additionally, DEA materials can be tuned to match the mechanical properties of soft substrates, enabling gentle and conformable actuation desirable for skin-interactive devices. However, a longstanding challenge remains the requirement for relatively high operating voltages to achieve significant deformation, which complicates low-power wearable integration. Thermal actuators, including thin-film heaters and thermoelectric elements, provide tactile sensations by dynamically altering temperature at the skin interface. These methods stimulate thermo receptive nerve endings and can be combined with vibrotactile cues to enrich haptic experiences. Thin-film thermal actuators use resistive heating to create localized temperature changes, whereas thermoelectric devices allow both heating and cooling based on current direction. While thermal stimuli introduce a complementary mode of sensation, thermal actuators typically exhibit slower temporal dynamics and higher power consumption compared with electromagnetic or electrostatic actuation, making them more suitable for applications where temperature feedback is integral (e.g., thermal realism in virtual environments) rather than high-frequency vibration.

Electrical Stimulation

In addition to mechanical and material deformation-based methods, electrical stimulation directly interfaces with the nervous system to evoke tactile perception. Transcutaneous electrical nerve stimulation (TENS) is a non-invasive technique that applies controlled electrical currents through surface electrodes to activate cutaneous and subcutaneous nerve fibers (Figure 2).

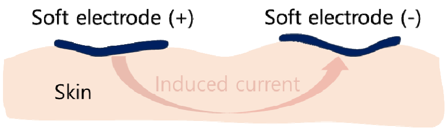

Figure 2. Schematic showing the soft electrodes attached on the skin for TENS

TENS has a long history in clinical therapy for pain modulation, yet its adaptation to haptic feedback systems leverages its ability to elicit sensory sensations that mimic touch or vibration [16]. Its advantages include minimal mechanical components, reduced weight, and the potential for fine-grained control of stimulation parameters such as pulse amplitude, width, and frequency, allowing modulation of perceived sensation quality and intensity. TENS is particularly appealing for closed-loop sensory feedback in prosthetics and wearable haptics, where the direct stimulation of afferent pathways can convey rich information about contact events or surface properties. Closely related is electrotactile stimulation, in which low-level electrical currents produce perceptions of pressure, tingling, or vibration by activating mechanoreceptive pathways in the skin [17]. Electrotactile feedback systems are often lightweight and energy-efficient when compared to traditional vibrotactile actuators, making them suitable for portable haptic interfaces. However, electrotactile methods face challenges related to individual differences in skin impedance, comfort thresholds, and the complexity of stimulus parameter optimization needed to elicit naturalistic sensations across different users. Research in this domain continues to explore electrode design, waveform engineering, and parameter tuning to improve the precision and user experience of electrically stimulated tactile feedback.

Soft and biocompatible materials

Soft and biocompatible materials are essential components of next-generation wearable and implantable bioelectronic systems, determining mechanical compliance, biological safety, and long-term device reliability. These materials must exhibit appropriate elasticity, chemical stability, and biocompatibility. This section reviews representative substrate materials, conductive components, and encapsulation strategies widely used in soft bioelectronics.

Substrate materials

Substrate materials serve as the mechanical basis of soft bioelectronic systems. Structural support while maintaining conformal contact with soft biological tissues is critical properties for improving the performances of bioelectronic

Elastomeric Polymers: Elastomeric polymers such as polydimethylsiloxane (PDMS), Ecoflex, and polyurethane are widely used due to their low Young’s modulus, high stretchability, and excellent biocompatibility. PDMS is particularly used in wide range of applications for its optical transparency, chemical stability, and ease of micro fabrication. Similarly, Ecoflex exhibits ultra-low modulus and high elongation, making it suitable for skin-like devices. One of promising elastomer, polyurethane consisting of urea functional group offers improved abrasion resistance and tunable mechanical properties. These elastomers typically exhibit Young’s moduli ranging from tens of kilopascals to several megapascals, enabling mechanical compatibility with human skin and soft tissues.

Hydrogels: Hydrogels, consisting of hydrophilic polymer networks capable of embedding large amounts of water. Their high-water content provides tissue-like softness and permeability to ions and metabolites, enabling low impedance via ionic conduction mechanism. Generally, hydrogels show high biocompatibility, low interfacial impedance, and excellent conformability, which is biological requirements for having intimate interfaces between biotic/abiotic components. However, challenges remain in improving their mechanical robustness and preventing dehydration under ambient conditions. One of recent study has focused on double-network and nanocomposite hydrogels to enhance toughness and durability [18]. In here, they presented the high toughness hydrogel through cross-linking of two different polymer chains (PAAM, Alginate).

Ultra-Thin Polymer Films: Ultra-thin polymer films, such as parylene-C and polyimide (PI), are widely used as substrate and encapsulation layers in flexible and stretchable electronic systems. These materials combine relatively high intrinsic Young's modulus (~GPa range) with excellent chemical and thermal stability. However, when their thickness is reduced to the micrometer or sub-micrometer scale, the effective bending stiffness decreases dramatically. As a result, even mechanically stiff polymers can exhibit highly mechanical compliant, skin-conformal behavior when fabricated as ultra-thin films. Parylene-C, deposited via chemical vapor deposition (CVD), offers pinhole-free conformal coating, excellent moisture barrier properties, chemical inertness, and proven biocompatibility. These features make it particularly attractive for implantable bioelectronics and epidermal sensors operating in humid or biofluid environments. For example, parylene-C has been used as both substrate and encapsulation material in implantable neural interfaces and long-term wearable biosensors due to its low water vapor transmission rate and cytocompatibility [19, 20].Polyimide, on the other hand, exhibits high thermal stability (often >300 °C), mechanical robustness, and compatibility with standard microfabrication processes. Its thermal endurance enables integration with high-density metal interconnects and semiconductor components using photolithography and sputtering techniques. Polyimide-based flexible printed circuit boards (FPCBs) and neural electrode arrays demonstrate stable electrical performance under repeated bending and stretching [21,22].Importantly, at thicknesses below approximately 5 µm, both parylene-C and polyimide films can achieve bending radii comparable to those of human skin without mechanical failure. This thickness-dependent flexibility enables intimate skin contact, reduced interfacial strain, and improved signal fidelity in electrophysiological recordings such as ECG and EMG.

Mechanical Matching to Biological Tissues: Mechanical mismatch between devices and skin can cause discomfort, delamination, and signal instability. Human skin typically exhibits a Young's modulus in the range of approximately 60 kPa to 1 MPa, depending on anatomical location and measurement conditions. Therefore, substrate materials are often engineered to fall within this range through material selection, structural design, and thickness control. Mechanical matching is essential for minimizing strain concentration and ensuring long-term wearability.

Conductive materials

Conductive materials have a central role in soft bioelectronic systems by enabling signal acquisition, transmission, and electrical stimulation under continuous mechanical deformation. Unlike conventional rigid materials, soft bioelectronics based on soft materials require conductors that can maintain electrical conductivity under stretching, bending, and twisting. To address this challenge, various material classes and structural engineering strategies have been developed.

Metal Films and Serpentine Structures: Thin metal films based on gold (Au), silver (Ag), and copper (Cu) are widely employed due to their high electrical conductivity and chemical stability. However, these metals are intrinsically brittle and prone to cracking under tensile strain when deposited on soft substrates. To improve stretchability, metal interconnects are commonly designed in serpentine, horseshoe, or fractal geometries. These structures accommodate applied strain through geometric unfolding and out-of-plane buckling, rather than direct material elongation. As a result, strains exceeding 30–100% can be achieved without electrical failure. Kim et al. reported wavy metal structures fabricated via pre-strain engineering, which showed excellent mechanical durability under repeated deformation [23]. In addition, nano-cracked metal films and metal–polymer composites have been developed to improve flexibility while retaining high conductivity. These approaches enable scalable fabrication using conventional deposition and lithography techniques.

Conductive Polymers: Conductive polymers represent an important class of soft conductors due to their intrinsic flexibility and biocompatibility. Among them, poly(3,4-ethylenedioxythiophene): polystyrene sulfonate (PEDOT:PSS) is the most widely used material in bioelectronics (Figure3).PEDOT:PSS exhibits mixed ionic–electronic conductivity, which is particularly advantageous for bio-interfacing applications where ion-to-electron transduction is required. This property enables low interfacial impedance and high signal-to-noise ratios in electrophysiological measurements. Rivnay et al. demonstrated that PEDOT:PSS-based organic electrochemical transistors can achieve high transconductance for neural and cardiac monitoring [24]. Khodagholy et al. reported flexible neural probes based on PEDOT:PSS, showing improved recording stability compared to metal electrodes [25].Various post-treatments, such as solvent annealing and acid doping, have been employed to enhance conductivity above 1000 S cm^{-1}. Composite approaches combining PEDOT:PSS with elastomers or hydrogels have further improved mechanical durability. However, conductive polymers generally exhibit lower conductivity and poorer environmental stability than metals, which limits their use in high-power applications.

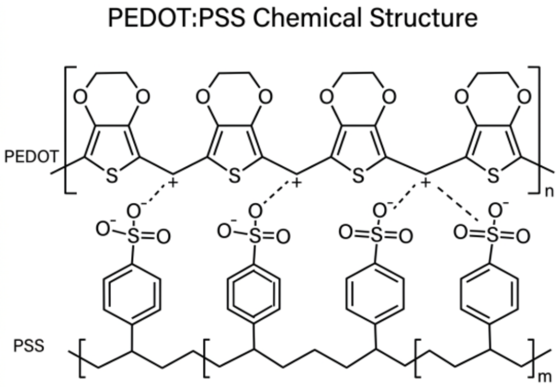

Figure 3. Chemical structure of PEDOT:PSS

Ionic Conductors: Ionic conductors transport electrical signals via ion migration and are typically based on ionogels or salt-doped hydrogels. These materials exhibit high stretchability, transparency, and excellent compatibility with aqueous biological environments. Ionogels consist of ionic liquids confined within polymer networks, providing wide electrochemical windows and low volatility. Salt-doped hydrogels, such as NaCl-doped PAAm or PVA gels, achieve high ionic conductivity while maintaining tissue-like softness.Yuk et al. reported highly stretchable ionic hydrogel electrodes for wearable sensors, showing stable performance under 500% strain [26]. Keplinger et al. demonstrated dielectric elastomer actuators and sensors using ionic hydrogel electrodes [27].Ionic conductors are particularly attractive for artificial skin, pressure sensors, and soft actuators. However, their relatively slow response and sensitivity to dehydration and temperature variations remain key limitations.

Conclusion

In conclusion, the development of soft and biocompatible haptic and bioelectronic systems has enabled significant progress toward seamless integration between electronic devices and the human body; however, several critical challenges remain, including reliable adhesives and encapsulation strategies, mechanically optimized designs for conformal contact, high spatial resolution and actuator density, efficient power management and wireless communication, long-term durability under repeated deformation, and sustained comfort for prolonged wear. Addressing these issues is essential for realizing practical applications in virtual and augmented reality, prosthetics and sensory restoration, telemedicine and assistive technologies, human–robot interaction, and continuous health monitoring. Looking forward, future research is expected to focus on the development of advanced functional materials such as two-dimensional materials and self-healing polymers, AI-driven personalized haptic rendering systems, multimodal integration for sensory augmentation, and highly miniaturized system-on-patch architectures. Furthermore, systematic efforts toward clinical translation, standardization, and regulatory approval will be crucial for bridging the gap between laboratory demonstrations and real-world deployment. Through interdisciplinary collaboration among materials science, electronics, data science, and medicine, next-generation soft bioelectronic platforms are anticipated to play a transformative role in human-centered technologies and digital healthcare.

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REFERENCES

1. Johansson, R.S. & Flanagan, J.R. (2009). Coding and use of tactile signals from the fingertips in object manipulation tasks. *Nature Reviews Neuroscience*, 10(5), 345-359.
2. Abraira, V.E. & Ginty, D.D. (2013). The sensory neurons of touch. *Neuron*, 79(4), 618-639.
3. Okamura, A.M., Dennerlein, J.T., & Howe, R.D. (2001). Vibration feedback models for virtual environments. *IEEE International Conference on Robotics and Automation*, 674-679.
4. Culbertson, H., Schorr, S.B., & Okamura, A.M. (2018). Haptics: The present and future of artificial touch sensation. *Annual Review of Control, Robotics, and Autonomous Systems*, 1, 385-409.
5. Kim, D.H., et al. (2011). Epidermal electronics. *Science*, 333(6044), 838-843.
6. Rogers, J.A., Someya, T., & Huang, Y. (2010). Materials and mechanics for stretchable electronics. *Science*, 327(5973), 1603-1607.
7. Dagdeviren, C., et al. (2013). Conformal piezoelectric energy harvesting and storage from motions of the heart, lung, and diaphragm. *Proceedings of the National Academy of Sciences*, 111(5), 1927-1932.
8. Koh, A., et al. (2016). A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. *Science Translational Medicine*, 8(366), 366ra165.
9. Jung, Y.H., Kim, J.H. & Rogers, J.A. (2021). Skin-integrated vibrohaptic interfaces for virtual and augmented reality. Advanced Functional Materials, 31(39), 2008805.
10. Kanitakis, J. (2002). Anatomy, histology and immunohistochemistry of normal human skin. European Journal of Dermatology, 12(4), 390–399.
11. Johnson, K.O. (2001). The roles and functions of cutaneous mechanoreceptors. Current Opinion in Neurobiology, 11(4), 455–461.
12. Gescheider, G.A., Bolanowski, S.J. & Hardick, K.R. (2001). The frequency selectivity of information-processing channels in the tactile sensory system. Somatosensory & Motor Research, 18(3), 191–201.
13. Choi, S. & Kuchenbecker, K.J. (2013). Vibrotactile display: Perception, technology, and applications. Proceedings of the IEEE, 101(9), 2093–2104.
14. Morgan, N.B. (2004). Medical shape memory alloy applications the market and its products. Materials Science and Engineering A, 378(1–2), 16–23.
15. Pelrine, R., Kornbluh, R., Pei, Q. & Joseph, J. (2000). High-speed electrically actuated elastomers with strain greater than 100%. Science, 287(5454), 836–839.
16. Melzack, R. & Wall, P.D. (1965). Pain mechanisms: A new theory. Science, 150(3699), 971–979.
17. Kaczmarek, K.A., Webster, J.G., Bach-y-Rita, P. & Tompkins, W.J. (1991). Electrotactile and vibrotactile displays for sensory substitution systems. IEEE Transactions on Biomedical Engineering, 38(1), 1–16.
18. Sun, J.Y., Zhao, X., Illeperuma, W.R.K., Chaudhuri, O., Oh, K.H., Mooney, D.J., Vlassak, J.J. & Suo, Z. (2012). Highly stretchable and tough hydrogels. Nature, 489(7414), 133–136.
19. Kim, D.-H., Kim, Y.-S., Wu, J., Liu, Z., Song, J., Kim, H.-S., Huang, Y.Y., Hwang, K.-C. & Rogers, J.A. (2009). Ultrathin silicon circuits with strain-isolation layers and mesh layouts for high-performance electronics on fabric, vinyl, leather, and paper. *Advanced Materials*, 21(36), 3703–3707.
20. Xu, S., Zhang, Y., Jia, L., Mathewson, K.E., Jang, K.-I., Kim, J., Fu, H., Huang, X., Chava, P., Wang, R., Bhole, S., Wang, L., Na, Y.J., Guan, Y., Flavin, M., Han, Z., Huang, Y. & Rogers, J.A. (2014). Soft microfluidic assemblies of sensors, circuits, and radios for the skin. *Science*, 344(6179), 70–74.
21. Someya, T., Sekitani, T., Iba, S., Kato, Y., Kawaguchi, H. & Sakurai, T. (2004). A large-area, flexible pressure sensor matrix with organic field-effect transistors for artificial skin applications. *Nature Materials*, 3(7), 464–470.

22. Jeong, J.-W., Yeo, W.-H., Akhtar, A., Norton, J.J.S., Kwack, Y.-J., Li, S., Jung, S.-Y., Su, Y., Lee, W., Xia, J., Cheng, H., Huang, Y., Choi, W.-S., Bretl, T., Rogers, J.A. & Rogers, J.A. (2013). Materials and optimized designs for human-machine interfaces via epidermal electronics. *Advanced Materials*, 25(47), 6839–6846.
23. Kim, D.-H., Song, J., Choi, W.M., Kim, H.-S., Kim, R.-H., Liu, Z., Huang, Y.Y., Hwang, K.-C., Zhang, Y. & Rogers, J.A. (2008). Materials and noncoplanar mesh designs for integrated circuits with linear elastic responses to extreme mechanical deformations. *Proceedings of the National Academy of Sciences*, 105(48), 18675–18680.
24. Rivnay, J., Inal, S., Salleo, A., Owens, R.M., Berggren, M. & Malliaras, G.G. (2018). Organic electrochemical transistors. Nature Reviews Materials, 3(2), 17086.
25. Khodagholy, D., Doublet, T., Gurfinkel, M., Quilichini, P., Ismailova, E., Leleux, P., Herve, T., Sanaur, S. &Malliaras, G.G. (2013). Highly conformable conducting polymer electrodes for in vivo recordings. *Nature Communications*, 4, 1575.
26. Yuk, H., Zhang, T., Lin, S., Parada, G.A. & Zhao, X. (2016). Tough bonding of hydrogels to diverse non-porous surfaces. Nature Materials, 15(2), 190–196.
27. Keplinger, C., Sun, J.-Y., Foo, C.C., Rothemund, P., Whitesides, G.M. & Suo, Z. (2013). Stretchable, transparent, ionic conductors. Science, 341(6149), 984–987.

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