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Topical Review

Constructing the haptic interaction loop for immersive VR/AR systems

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Abstract

The pursuit of hyper-realistic immersive virtual and augmented reality is fundamentally bottlenecked by the 'Ghost Hand' phenomenon, a severe sensory mismatch between advanced audio-visual rendering and impoverished physical interaction. To eliminate this asymmetry, this review conceptualizes a closed-loop 'Human-Machine-Environment' haptic interaction framework comprising sensing, processing, and feedback. Distinct from existing reviews that merely regard flexibility as a basic material advantage, this work centers on the system-level engineering realization of complete haptic interactive loops. We systematically evaluate the continuous evolution of hardware architectures toward imperceptible, flexible electronic skins. At the input terminal, we explore how bio-inspired microstructures and novel transduction mechanisms enable multimodal signal decoupling and high-fidelity sensory digitization. For the output terminal, we analyze advancements in kinesthetic, cutaneous, and thermal haptic actuation that physically reconstruct digital stimuli for the human nervous system. Furthermore, we highlight the integration of these components into intelligent wearable systems, where deep learning architectures and in-sensor edge computing overcome the inherent nonlinearity and latency of soft materials. Finally, we validate this closed-loop framework across diverse applications, including robotic teleoperation, medical rehabilitation, and immersive

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entertainment, while delineating the remaining engineering challenges surrounding the power-portability paradox and multimodal crosstalk. Ultimately, this review establishes that closing the physical haptic loop is the requisite cornerstone for transitioning from passive observation to fully embodied, active interaction in the metaverse.

Keywords: flexible electronic skins, soft functional materials, haptic interaction, flexible tactile sensing, multimodal haptic feedback

1. Introduction

Driven by unprecedented strides in near-eye display technologies, modern head-mounted displays (HMDs) are approximating the physiological limits of the human eye in terms of single-eye resolution, refresh rates, and field of view [1–4]. When coupled with advanced spatial audio, virtual reality (VR) and augmented reality (AR) systems have largely satisfied the 'audio-visual Turing test', creating highly realistic digital twin environments [5–7]. However, a stark asymmetry persists between this hyper-realistic audio-visual immersion and the impoverished state of physical interaction, resulting in a severe sensory mismatch [8, 9]. The most critical bottleneck in current VR experiences is the 'Ghost Hand' effect, which is a phenomenon where users visually perceive virtual objects but remain physically detached from them. Attempts to grasp or touch virtual entities result in unnatural visual interpenetration without necessary contact confirmation or physical compliance [10, 11]. This sensory conflict not only shatters the user's sense of immersion and defies the brain's cognitive expectations of the physical world but also serves as a primary catalyst for cybersickness [12, 13]. As highlighted by Yu *et al*, although the skin constitutes the human body's largest sensory organ and the primary interface for connecting the physical and digital realms, it remains largely 'silent' in current immersive systems [14]. Exclusive reliance on audio-visual stimuli restricts users to 'passive observation', failing to satisfy the innate human drive for 'active physical interaction'. Consequently, VR/AR technologies are undergoing a profound paradigm shift: transitioning from superficial optical simulation to the construction of a full-sensory metaverse incorporating mechanical, thermal, and textural dimensions [15–17]. In this context, tactile sensing is no longer a mere visual appendage, but the fundamental cornerstone for establishing physical laws in virtual worlds and eliminating the 'Ghost Hand' phenomenon. The integration of tactile interaction is not merely a technical additive but a fundamental requirement to bridge the sensory gap between digital information and human perception. Its core value operates on a continuum from psychological embodiment to functional dexterity. From a psychophysical perspective, the establishment of body ownership, which is the illusion that a virtual avatar is one's own, relies strictly on the spatiotemporal alignment of visual and tactile cues [18, 19]. As demonstrated by Zhang *et al* [20] and Kim *et al* [21], only when tactile feedback provides synchronous sensory confirmation can the brain's multisensory integration mechanism eliminate the uncanny valley effect and validate the physical existence of virtual objects [22, 23]. Crucially, this sensory confirmation directly dictates operational performance. In the absence of physical constraints and force feedback, users suffer from depth perception errors and an inability to modulate grasping force, leading to the 'Ghost Hand' phenomenon. Song *et al* [24] highlight that tactile signals provide the necessary boundary conditions for closed-loop motor control, significantly reducing error rates in fine manipulation tasks [25, 26]. Thus, high-fidelity tactile sensing is the prerequisite for transforming VR/AR from a passive display medium into an active, functional workspace.

To resolve the aforementioned sensory conflicts and realize these theoretical values of embodiment and dexterity, it is imperative to establish a closed-loop information flow across the 'Human-Machine-Environment'. This review conceptually deconstructs the haptic system into a tripartite haptic interaction loop comprising sensing, processing, and feedback. As the genesis of interaction, the sensing stage requires high-density sensor arrays to digitally capture user intent, including pose and gestures, alongside contact states such as pressure and physiological signals. This raw data is then transmitted to the processing stage, the computational core where algorithms, ranging from physics engines to machine learning models, that is parse sensory inputs to calculate physical interactions between virtual objects and the user's avatar. Finally, the cycle concludes with feedback, where actuators convert digital signals back into physical stimuli to complete the sensory circuit [27, 28]. Within this framework, high-precision, low-latency sensing serves as the absolute prerequisite; without the accurate digital reconstruction of physical contact, any subsequent feedback lacks a valid foundation. Underpinning this theoretical loop is a profound physical transformation of hardware architectures from rigid to flexible forms. The field has evolved from an initial phase of rigid interfaces, dominated by traditional controllers and bulky exoskeletons that, while capable of force feedback, constrained user freedom and lacked fine cutaneous sensitivity. With advances in materials science, the technology progressed to flexible wearables, where fabric-based data gloves significantly improved ergonomic comfort. Currently, the field is advancing toward electronic skin (e-skin) [29]. As envisioned by Strzalkowski *et al*, skin-integrated interfaces utilize ultra-thin, stretchable electronics to achieve imperceptible wear [30]. Leveraging wireless technologies for control and power, these devices function not as external accessories but as a second skin, enabling seamless, all-day sensory augmentation [31, 32]. However, the paradigm shift toward soft, stretchable e-skins introduces critical challenges, particularly regarding

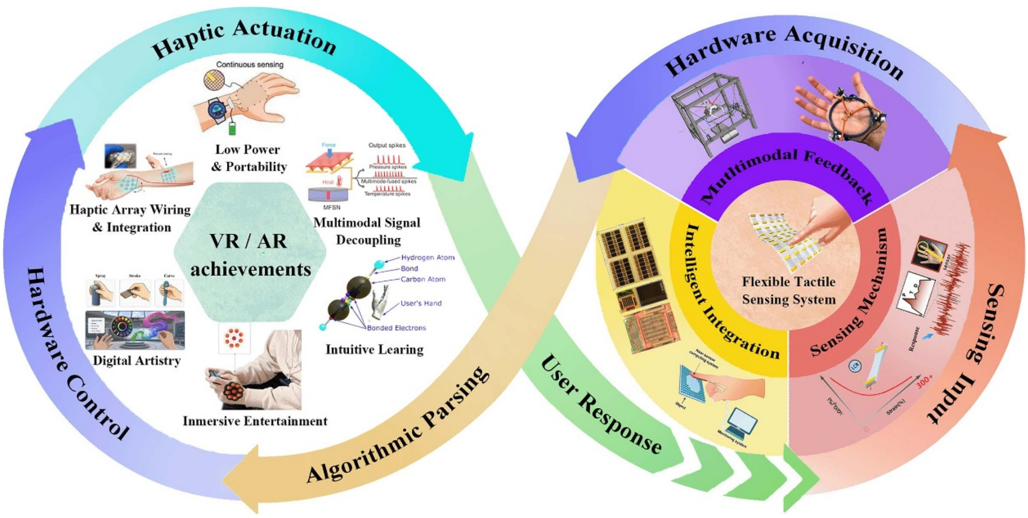

Figure 1. Overview of closed-loop integrated flexible tactile systems for VR/AR, from underlying sensing mechanisms to broad applications and prospects. Reproduced with permission [35]. Copyright 2022, ACS. Adapted with permission [36]. Copyright 2025, Elsevier. Reproduced with permission [37]. Copyright 2019, IEEE. Reproduced with permission [38]. Copyright 2011, Cambridge University Press. Reproduced with permission [39]. Copyright 2025, Springer Nature. Reproduced with permission [40]. Copyright 2022, Wiley-VCH. Adapted with permission [41]. Copyright 2019, Springer Nature. Adapted with permission [14]. Copyright 2019, Springer Nature. Adapted with permission [42]. Copyright 2021, Wiley-VCH. Reproduced with permission [43]. Copyright 2025, Springer Nature. Adapted with permission [44]. Copyright 2022, Wiley-VCH.

how to achieve sensing capabilities comparable to, or surpassing, biological skin within ultrathin form factors while mitigating the inherent hysteresis and nonlinearity of soft materials [33, 34]. With sensing established as the critical initiation node of the interaction loop, the fidelity of signal acquisition directly dictates the quality of the entire system. To eliminate the 'Ghost Hand' effect, the core challenge of precisely translating complex physical fields into computable digital signals must be resolved.

Existing review literatures on flexible e-skins and haptic interaction predominantly focus on isolated advances in functional materials, individual transduction mechanisms, or separate tactile sensing and actuation devices, while seldom establishing a systematic logical connection across the full technical chain. Most previous works merely regard flexibility and soft electronics as an underlying enabling material technology, rather than exploring their essential role in supporting the complete construction of haptic interactive systems. Differentiated from these conventional summaries, this review highlights the system-level closed-loop implementation of human-machine-environment haptic interaction as its core proposition, and further clarifies how flexible e-skins act as the indispensable hardware foundation to underpin the integrated loop of sensing acquisition, signal processing, and haptic feedback.

Herein, this review aims to construct a haptic interaction loop, whose full closed-loop architecture is visualized in figure 1, positing that high-fidelity sensory digitization is the prerequisite for realistic physical reconstruction in the metaverse. Initially, section 2 challenges the limitations of conventional rigid sensors by focusing on biomimetic sensing mechanisms, explaining how emerging approaches achieve multimodal decoupling and high spatiotemporal resolution in flexible forms. Furthermore, section 3 shifts focus to the physical reproduction of these signals. It analyzes the transition from symbolic vibration to high-fidelity multimodal feedback, discussing how soft and rigid actuators bridge the gap between digital bits and biological perception. Thereafter, section 4 unifies these elements into intelligent integrated systems, illustrating how deep learning architectures and edge computing empower wearables, from gloves to imperceptible e-skins, to overcome the inherent nonlinearity of soft materials and achieve real-time sensing-computing synergy. Subsequently, section 5 validates the efficacy of this closed-loop framework through critical application scenarios, demonstrating how haptics establishes force transparency in robotic teleoperation and induces neural plasticity in medical rehabilitation. Finally, section 6 confronts the remaining engineering barriers before the conclusion envisions the ultimate evolution toward self-healing, bio-integrated interfaces and brain–computer fusion.

2. The input terminal: mechanisms for flexible tactile sensing

In constructing the 'Human-Machine-Environment' full-sensory interaction loop, tactile sensing plays the pivotal role of the input terminal. Figure 2 outlines mainstream flexible tactile sensing technologies with full classification. Having articulated the urgent demand for haptic immersion, this analysis delves into the micro-physical level, examining how to precisely translate complex physical fields (normal force, shear force, textural vibration) and thermodynamic fields (temperature) into computable digital signals. As the sensory cornerstone of the interaction system, the sensor's sensitivity, multimodal decoupling capability, and mechanical impedance

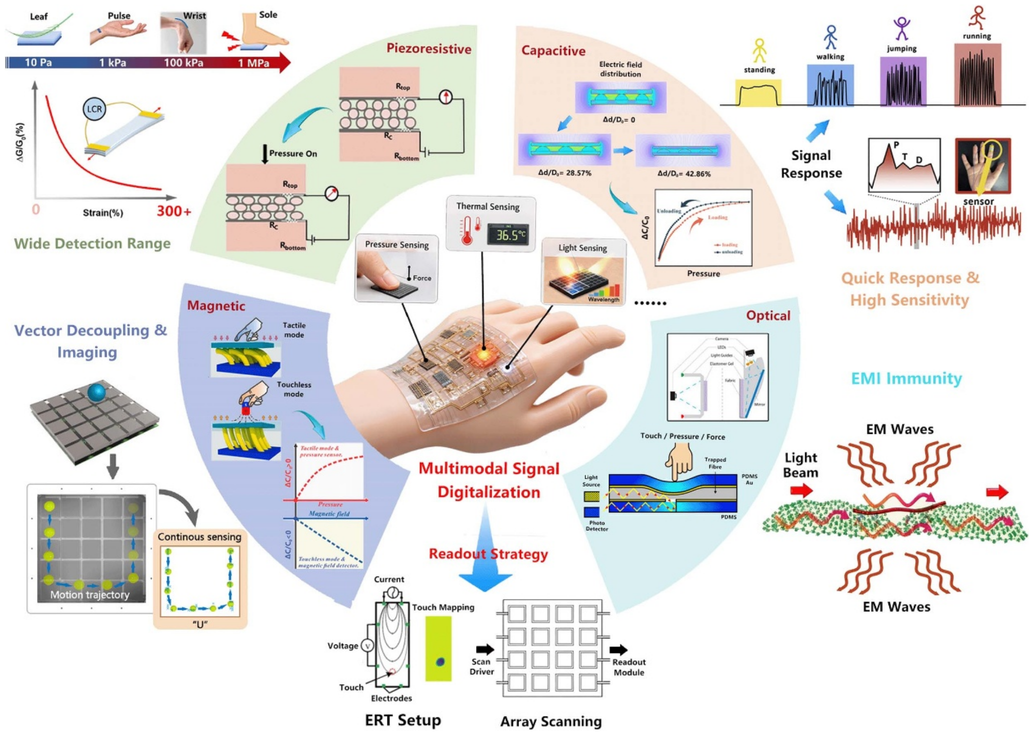

Figure 2. Classification and performance overview of flexible tactile sensors as the input terminal for full-sensory human-machine interaction. Reproduced with permission [35]. Copyright 2022, ACS. Reproduced with permission [46]. Copyright 2022, Chinese Academy of Sciences. Adapted with permission [36]. Copyright 2025, Elsevier. Reproduced with permission [47]. Copyright 2024, Springer Nature. Reproduced with permission [48]. Copyright 2020, Elsevier. Adapted with permission [49]. Copyright 2025, IEEE. Reproduced with permission [50]. Copyright 2018, IEEE. Adapted with permission [51]. Copyright 2024, Wiley-VCH.

matching with human skin directly dictate the fidelity of subsequent haptic feedback and provide the necessary physical data foundation for intelligent algorithmic processing [45]. Without reliable digitization at this stage, every downstream stimulus reverts to the Ghost Hand condition, regardless of how realistic the visual rendering is.

2.1. Enhancing piezoresistive and capacitive sensing via bio-inspired microstructures

As the foundational pillars of tactile digitization, piezoresistive and capacitive sensors dominate the field due to their mature readout circuitry and fabrication scalability [52–54]. Piezoresistive sensors, which transduce mechanical stimuli into resistance variations, offer simple signal processing and wide detection ranges but often suffer from significant hysteresis and temperature drift [55]. Conversely, capacitive sensors, which detect changes in capacitance (voltage) induced by geometric deformation or dielectric variation, provide high sensitivity and low power consumption but are susceptible to parasitic noise and limited sensitivity in traditional planar configurations [56]. To reconcile the trade-off between sensitivity, linearity, and hysteresis in these traditional electrical mechanisms, researchers have looked to the epidermal-dermal junction of human skin, leveraging bio-inspired microstructures to optimize signal transmission efficiency. In the realm of piezoresistive sensing, the primary challenge lies in amplifying the contact resistance change under minute pressures while maintaining structural integrity under tension. Inspired by the interlocking ridge structure of human skin, Wang *et al* [57] designed a double-interlocked hexagonal prism array (figure 3(a)). This geometric enhancement drastically increases the effective contact area under compression, converting subtle pressure fluctuations into massive resistance variations, thereby substantially boosting the signal-to-noise ratio (SNR). Addressing the material stability of resistive networks, Choi *et al* [58] developed novel conductive nanocomposites to mitigate the physical issue of conductive network fracture under tension, ensuring stable electrical resistance outputs even during dynamic stretching (figure 3(b)). For capacitive sensing, enhancing the dielectric response and electrode efficiency is key to breaking sensitivity limits. Zhu *et al* [59] proposed a micro-honeycomb electrode design that optimizes charge distribution via a multi-contact mechanism, effectively resolving the low-sensitivity bottleneck inherent to traditional planar electrodes (figure 3(c)). Furthermore, Gao *et al* [60] utilized a gravity-driven self-assembly process to construct gradient-structured MBene/rGO/PUF sensors with vertically layered conductive networks (figure 3(d)). This unique gradient architecture effectively induces the Maxwell–Wagner polarization effect to strengthen interfacial dielectric polarization, not only improving the pressure detection range but also extending capabilities to non-contact proximity sensing by detecting fringing field disturbances. Beyond specific transduction mechanisms, optimizing interface mechanics is critical for minimizing signal hysteresis,

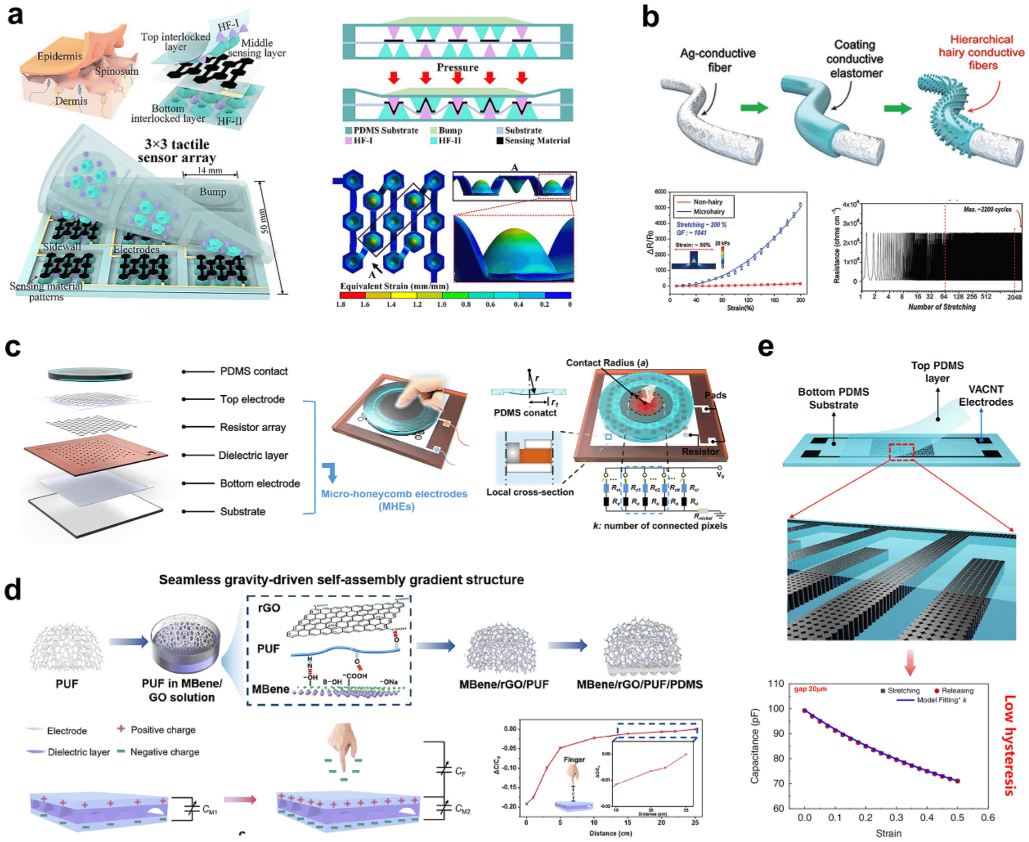

Figure 3. Bio-inspired microstructured piezoresistive and capacitive tactile sensors for enhanced performance. (a) Schematic of dual-interlocked flexible tactile sensor, bioinspired by human skin's interlocking ridge structure. It features a 3 × 3 array of sensing units with double-interlocked hexagonal prism (HF-I/HF-II) arrays, which maximize effective contact area under compression to convert subtle pressure into significant resistance changes. Reproduced with permission [57]. Copyright 2022, IEEE. (b) Schematic illustrating the hierarchical micro hairy conductive fiber structure alongside sensing performance characteristics showing distinct sensitivity responses at different lateral strain levels and multiple stretching cycles with strain ≈30%. Reproduced with permission [58]. Copyright 2019, Wiley-VCH. (c) Schematic of the multi-contact capacitive tactile sensor with micro-honeycomb electrodes alongside its equivalent circuit under touch force, where optimized charge distribution via multi-contact mechanism enhances its sensitivity compared to planar electrode. Reproduced with permission [59]. Copyright 2023, Elsevier. (d) Illustration of the fabrication process of the gradient-structured MBene/rGO/PUF dual-modal sensor, its touchless sensing working principle, and dynamic capacitance variation during robotic finger-human finger interaction. Reproduced with permission [60]. Copyright 2025, Wiley-VCH. (e) Schematic illustrating the flexible strain sensor with 3D vertically aligned carbon nanotube interdigital electrodes alongside its output and hysteresis results fitted with the theoretical model ($k = 0.57$). Engineered micro-nano sensing interface reduces material viscoelastic loss, suppressing signal hysteresis (<0.35%) during large deformations for rapid dynamic response. Adapted with permission [61]. Copyright 2022, Springer Nature.

which is a common defect in soft viscoelastic polymers. Wang *et al* [61] explored the optimization of sensing interfaces at the micro-nano level. By engineering 3D electrode-substrate sensing interfaces to reduce the viscoelastic loss of materials, they effectively suppressed signal hysteresis during large deformations, ensuring rapid response speeds under dynamic loading (figure 3(e)). Despite these bio-inspired advances, traditional electrical sensors still face inherent challenges regarding temperature/humidity drift and often require complex computational decoupling to distinguish between normal and shear forces.

2.2. Vector decoupling and super-resolution via magnetic and magnetostrictive sensing

Addressing the physical limitations of electrical sensors in multidimensional force decoupling, magnetic sensors offer a new pathway for high-precision tactile digitization via their intrinsic vector characteristics and contactless mechanisms [62, 63]. Magnetic sensors (e.g. Hall effect, GMR) can naturally distinguish Normal Force from Shear Force by monitoring changes in the magnetic field vector. Furthermore, due to the permeability of magnetic fields, these sensors eliminate internal mechanical wear and exhibit extremely low hysteresis. Zhou *et al* [48] ingeniously designed a tilted magnetic micro-pillar array based on CIP/PDMS composite materials with tailored structural gradient characteristics (figure 4(a)). By exploiting the anisotropy of pillar deflection and magnetic response under pressure, this design achieved zero cross-talk differentiation between contact pressure and non-contact magnetic signals, which is a capability vital for precise manipulation in complex electromagnetic environments. In terms of dynamic sensing, Weng *et al* [64] utilized the inverse magnetostrictive effect of Fe–Ga alloys to

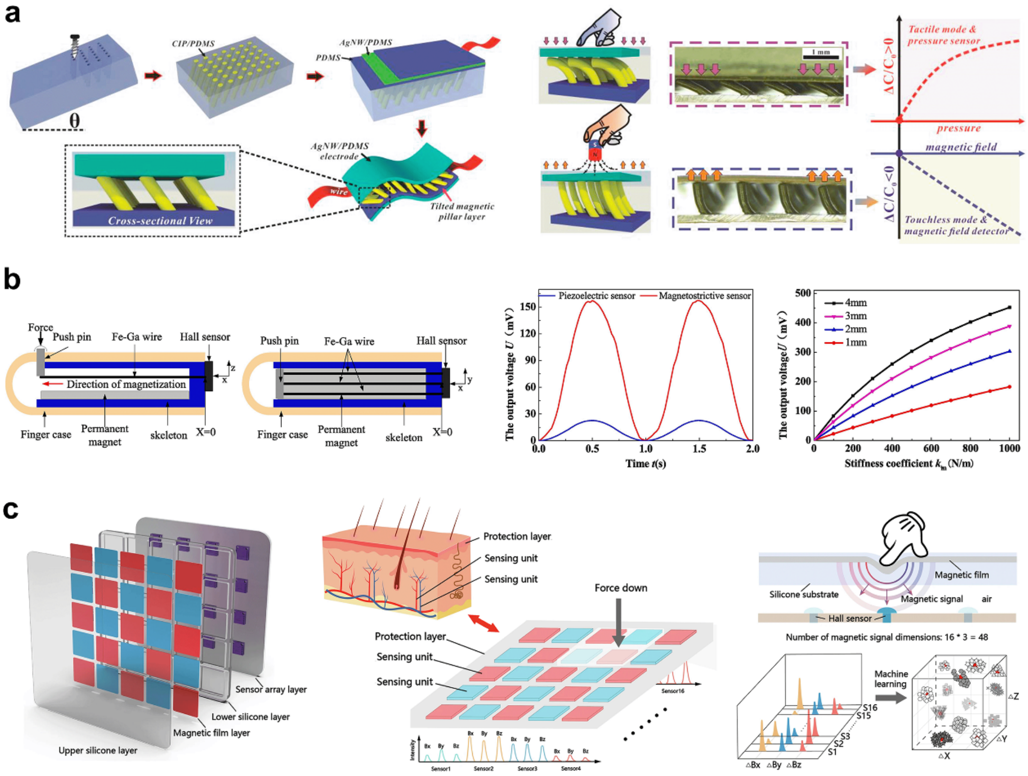

Figure 4. Magnetic and magnetostrictive tactile sensing for vector decoupling, dynamic detection and super-resolution positioning. (a) Schematic of dual-modal sensing through tilted magnetic micro-pillars' deflection-dependent signal response. Fabrication process shows tilted CIP/PDMS micro-pillars integrated with AgNW/PDMS electrodes. Working mechanisms demonstrate downward pillar deflection (positive $\Delta C/C_0$) for tactile pressure sensing, and upward deflection (negative $\Delta C/C_0$) for touchless magnetic field detection, enabling zero cross-talk. Reproduced with permission [48]. Copyright 2020, Elsevier. (b) Schematic of Fe–Ga magnetostrictive tactile sensor for dynamic force and stiffness detection. Force deforms magnetized Fe–Ga wires, with Hall sensors detecting stress-induced magnetic changes. Dynamic force response is tested under 1 Hz sinusoidal loading (vs piezoelectric sensor); stiffness detection uses varied push-pin depths (1–4 mm) to measure output voltage vs object stiffness (k_m). Reproduced with permission [64]. Copyright 2020, Elsevier. (c) Illustration of high-resolution magnetic skin. The multi-layer structure (silicone layers, magnetic film, sensor array) mimics human skin. Force-induced magnetic film deformation generates magnetic signals, which 16 Hall sensors (48-dimensional data) capture. Machine learning parses these signals to realize high-resolution positioning. Adapted with permission [47]. Copyright 2024, Springer Nature.

develop sensors capable of simultaneously detecting dynamic force and object stiffness (figure 4(b)). The physical mechanism relies on stress-induced magnetic domain flipping, granting the direct force–magnetic coupling high sensitivity to high-frequency textural vibrations. Additionally, to resolve the wiring bottleneck in high-density arrays, Hu *et al* [47] proposed a 'magnetic skin' concept. By combining a Hall sensor array with deep learning algorithms, they achieved millimeter-level super-resolution positioning using only sparse physical pixels by parsing the continuous variation of the magnetic field distribution (figure 4(c)). Compared to electrical solutions, magnetic sensing demonstrates significant advantages in shear force detection and fatigue resistance, though system integration must account for external magnetic interference shielding.

2.3. Electromagnetic interference (EMI) immunity and high-precision deformation sensing via optical mechanisms

In VR/AR systems, the dense electronic components within HMDs and controllers generate strong EMI. Optical sensors, leveraging the uncharged nature of photons, possess natural EMI Immunity, making them a crucial branch for high-fidelity sensing [65]. The core of optical sensing lies in modulating minute deformations via light intensity loss or wavelength shifts (gratings/interferometers) [66]. Wang *et al* [67] proposed a tactile sensor based on a Fiber Mach–Zehnder interferometer (MZI) (figure 5(a)). Utilizing the extreme sensitivity of optical path difference to deformation, it achieved sensitivity superior to traditional gratings in the 0–10 N range, making it particularly suitable for fine texture recognition. In terms of wearable form factors, Ando *et al* [68] demonstrated a non-occluding design: attaching optical sensors to the back of the hand to infer fingertip contact force via skin deformation and blood volume changes (PPG signals) (figure 5(b)). This counter-intuitive physical path preserves the bare-hand tactile sensitivity of the fingers while achieving force digitization. Furthermore, for smart textile applications, Ma *et al* [69] utilized the bending loss principle of optical micro-nanofibers to realize weaveable strain sensing, demonstrating the potential of photonics in flexible wearables (figure 5(c)). Although optical solutions excel in stability and corrosion resistance, the coupling and miniaturization of light sources

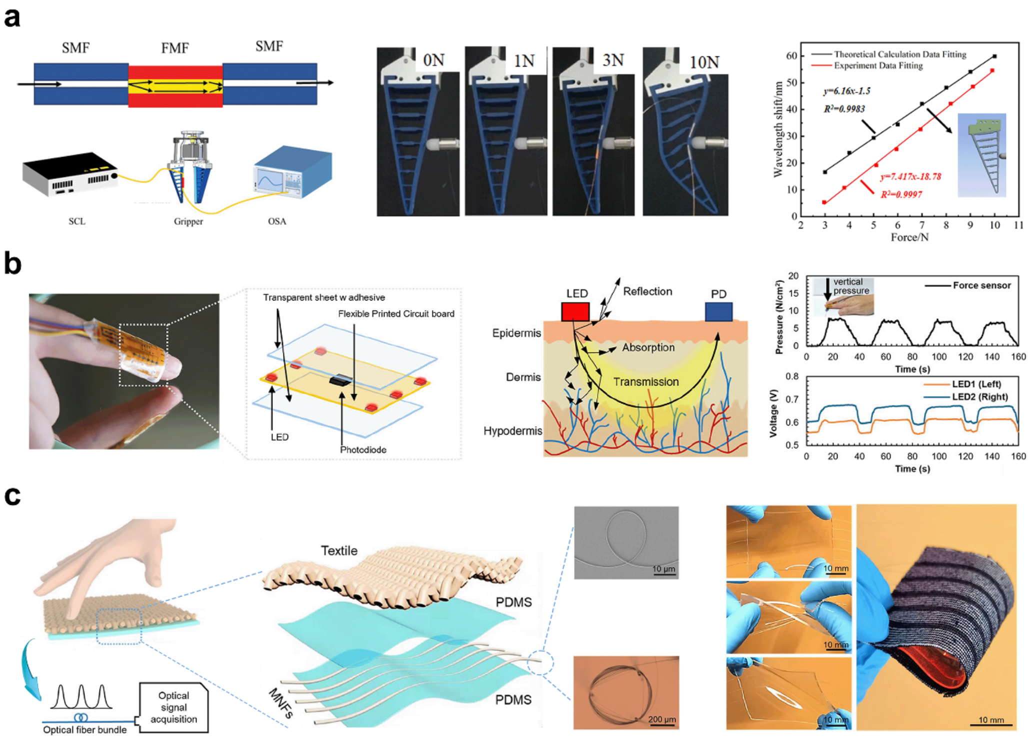

Figure 5. EMI-immune optical sensing solutions for high-precision deformation. (a) High-sensitivity tactile force sensing by fiber MZI. The sensor consists of SMF-FMF-SMF, integrated with a gripper and connected to an SCL light source and OSA detector. Gripper deformation under 0–10 N force is captured, and the wavelength shift (experimental vs theoretical fitting) shows high linearity, demonstrating the sensor's sensitivity to tactile force. Reproduced with permission [67]. Copyright 2024, IEEE. (b) Non-occluding fingertip force detection via back-of-hand optical sensor capturing skin deformation and light-blood interactions. The flexible FPC sensor (integrating LEDs and PD) adheres to the hand, leveraging light interactions (reflection, absorption, transmission) in skin layers to capture force-driven changes. Fingertip vertical pressure (top right) aligns with PD voltage responses (bottom right), enabling unobstructed tactile force digitization. Reproduced with permission [68]. Copyright 2025, IEEE. (c) Schematic of weaveable optical textile sensing leveraging micro-nanofiber bending loss. The textile-PDMS-MNF composite structure (with embedded MNFs) converts tactile interactions into optical signal changes. Fabrication and integration steps (right) show the wearable, flexible design, enabling strain sensing for smart textiles. Reproduced with permission [69]. Copyright 2022, Springer Nature.

and detectors remain engineering challenges for flexible optical circuit design [70].

2.4. System-level readout strategies for large-scale tactile sensing

When scaling tactile sensing from single-point devices to full-body e-skin, wiring clutter and signal crosstalk emerge as critical engineering bottlenecks [42, 71]. The reliance on traditional row-column scanning architectures results in a prohibitive increase in interconnect density as pixel counts surge. To circumvent this, Zheng *et al* [72] introduced electrical resistance tomography (ERT), an inverse problem-solving technique based on boundary value measurements (figure 6(a)). This study demonstrated that the pressure distribution across a large-area porous sponge could be reconstructed utilizing solely boundary electrodes, significantly minimizing internal wiring and providing a mathematical framework for the low-cost manufacturing of scalable skins. At the signal readout level, Büscher *et al* [73] developed low-power, moisture-resistant array scanning circuits for four-layer piezoresistive textiles (figure 6(b)). These innovations effectively resolved signal drift and crosstalk issues inherent to practical wearable environments, laying the essential groundwork for system-level integration.

In summary, tactile sensing technology has evolved from simple mechanical switches to digital skins possessing multimodality (force/magnetic/optical), high spatiotemporal resolution, and adaptability. Researchers have significantly enhanced sensor sensitivity and decoupling capabilities through bio-inspired structural enhancement, the introduction of magnetic/optical mechanisms, and gradient and composite material innovations. The breakthroughs in biomimetic tactile sensing have successfully achieved the precise mapping from physical contact to high-dimensional digital signals, resolving the digitization challenge at the input end of the interaction loop. However, in the complete 'Human-Machine-Environment' circuit, high-sensitivity sensing alone is insufficient to construct true immersion; the system must also possess the capability to inversely translate these digital bits into physical stimuli recognizable by the human nervous system.

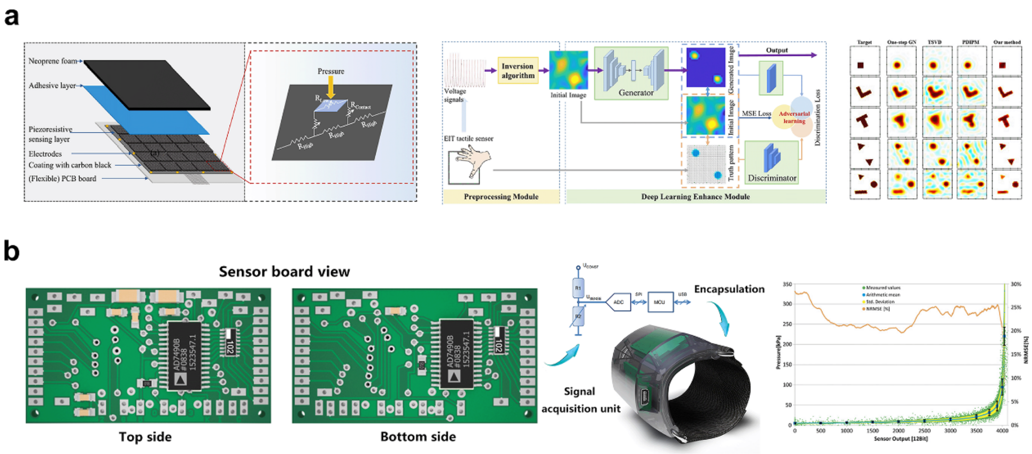

Figure 6. Strategies for scalable tactile sensing at the system readout level. (a) Schematic illustrating the structure of the ERT-based large-area tactile sensor, framework of the data-driven imaging method. Numerical simulations of five contact situations comparing the proposed ERT-based tactile imaging method with three conventional reconstruction algorithms (one-step GN, TSVD, PDIPM). Boundary electrode measurements enable pressure distribution reconstruction, minimizing internal wiring and delivering more accurate contact shape recovery. Reproduced with permission [72]. Copyright 2024, IEEE. (b) Photograph of the 16-channel ADC-equipped sensor board and its 3D-printed forearm-mounted electronics housing. The inset diagram shows the signal acquisition circuitry. Measured sensor performance over 150 000 data points and statistics confirms its reliable pressure measurement with low NRMSE and stable output. Adapted with permission [73]. Copyright 2015, Elsevier.

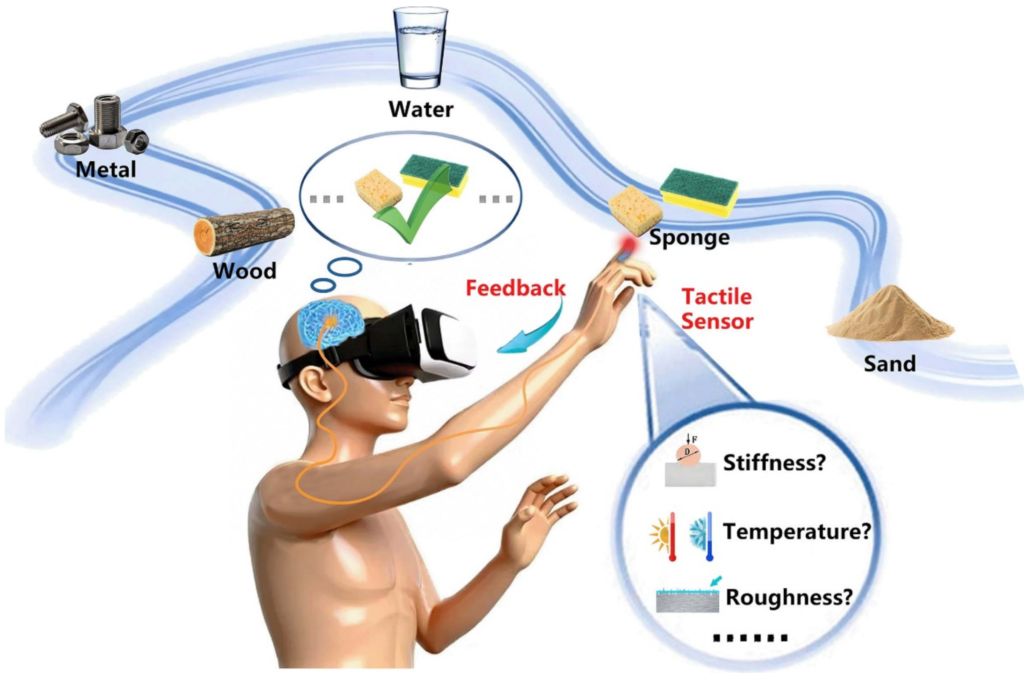

Figure 7. Schematic of multimodal haptic feedback for reconstructing physical sensory stimuli in human-machine-environment interaction. First, the tactile sensor captures physical stimuli from various real-world materials (e.g. metal, wood, water, sponge, sand), extracting key tactile features including stiffness, temperature, roughness, and other properties. These signals are then processed and reconstructed to simulate corresponding tactile sensations, which are delivered as feedback to the user via the haptic system, allowing the user to accurately distinguish and identify the target object from numerous options in the virtual interaction scenario. This enables the user to perceive realistic tactile cues within the virtual environment, thereby enhancing the sense of immersion and presence.

3. Multimodal haptic feedback and display technologies

While section 2 addressed the digitization of physical contact at the input end, true immersion within the ‘Human-Machine-Environment’ circuit demands the inverse capability: translating digital signals back into physical stimuli perceptible by the nervous system. Figure 7 illustrates the working principle of multimodal haptic feedback. As the output terminal, tactile feedback technology bears the core mission of bridging data acquisition with sensory reconstruction. As outlined in section 1, the Ghost Hand effect originates not from any single missing modality but from the absence of physical confirmation at the moment of virtual contact. The feedback technologies surveyed below are therefore evaluated against a single benchmark: how much of the contact confirmation deficit can each modality close?

3.1. Kinesthetic feedback via rigid parallel mechanisms and soft fluidic actuation

Kinesthetic feedback primarily targets proprioceptors in muscles, tendons, and joints, aiming to simulate object weight, inertia, grasping resistance, and surface hardness [74]. Technologically, the field currently exhibits a parallel development of rigid parallel mechanisms and soft fluidic actuation [75, 76]. Rigid parallel mechanisms excel in delivering high-stiffness and high-precision force vectors. Distinct from conventional serial structures prone to accumulated positioning errors, parallel configurations enable effective decoupling of normal and shear forces. Lykov *et al* [77] introduced DeltaFinger, a typical exoskeleton device utilizing a 3-RRR parallel structure to achieve three-dimensional force feedback at the fingertip (figure 8(a)). This design not only simulates normal pressing sensations but also accurately reproduces shear forces along the surface, thereby enhancing the perception of virtual textures and edges. Similarly, Trinitatova and Tsetserukou [37] developed DeltaTouch, further optimizing the kinematic model of wearable Delta mechanisms to improve fine manipulation flexibility while maintaining high-fidelity force feedback (figure 8(b)). However, the inherent drawbacks of rigid mechanisms lie in their structural complexity, bulk, and weight, which to some extent constrain the user's natural range of motion. To address portability and safety concerns, soft pneumatic and fluidic actuation technologies have emerged. These actuators possess intrinsic safety and high compliance. Qi *et al* [78] presented HaptGlove, representing the cutting edge of this direction (figure 8(c)). This system employs microfluidic pneumatic clutches (PneuClutch) and soft indenters, achieving a wireless, lightweight design of only 283 g. Adjustment of internal air pressure allows the system to dynamically tune fluid stiffness, enabling realistic reproduction of tactile feelings from soft sponge compression to rigid stone grasping. Although the response bandwidth of pneumatic systems is typically lower than that of motor drives, their superior ergonomic comfort makes them more suitable for extended VR interactions. Furthermore, for specific interaction scenarios, wire-driven and handheld controllers offer alternative solutions. Ko *et al* [79] designed BStick, a handheld linear actuator that, by changing internal slider length and damping, can provide up to 22 N of grasping resistance, effectively simulating the geometry and hardness of rigid objects (figure 8(d)). On a larger scale of full-body interaction, Karkoub *et al* [38] demonstrated a large-scale simulator based on cable drives, capable of providing full-body gravity and acceleration feedback in flight simulation scenarios through the synthesis of tension from multiple cables (figure 8(e)).

3.2. Cutaneous feedback through vibrotactile rendering and physical material reproduction

Distinct from kinesthetic feedback, cutaneous feedback focuses on stimulating the slow adapting and fast adapting mechanoreceptors on the skin surface to convey surface texture, roughness, and contact transients [30, 80]. Vibrotactile and illusion rendering remains the most mature technical path. Traditional linear resonant actuators (LRAs) often suffer from low information entropy, making it difficult to express complex textures [81]. To address this, Liu *et al* [82] proposed a data-driven rendering method, transforming real force signals acquired during industrial processing into high-frequency vibration waveforms, significantly enhancing operational realism (figure 9(a)). Concurrently, to break the physical limits of actuator array density, researchers have leveraged psychophysical effects for illusion rendering. Apostolou *et al* [83] utilized the funneling illusion, which is a phenomenon where simultaneous stimulation of two distinct points on the skin creates the sensation of a single phantom point located between them. This technique realizes continuous shifting phantom tactile stimuli via accurate modulation of the amplitude proportion among neighboring actuators, thus attaining high-resolution haptic presentation at a low hardware expense. In the realm of physical material reproduction, an innovative approach has emerged that transcends virtual simulation: the direct use of real materials. Maezono *et al* [84] developed the MateREAL system, which integrates 30 types of real material samples (e.g. sandpaper, silk, rubber) via a micro-scroll structure (figure 9(b)). The system dynamically switches the physical material at the fingertip contact point based on the VR scene, fundamentally resolving the frequency domain distortion problem inherent in vibration-simulated textures and providing realistic touch. The development of novel flexible actuators is dedicated to achieving 'invisible' wearability. Phung *et al* [85] demonstrated soft actuators based on dielectric elastomers, integrating sensing and actuation functions within a thin-film structure capable of outputting up to 600 mN of force with extremely fast response speeds (figure 9(c)). To solve the issue of lost bare-hand sensitivity due to fingertip coverage, Xu and Hasegawa [86] proposed a nail-mounted haptics solution, utilizing micro-motors to stimulate the fingernail sidewalls to simulate tangential forces on the finger pad (figure 9(d)). This non-contact design ingeniously preserves the original sensitivity of the finger. Additionally, Tanimichi *et al* [87] further improved the output performance of micro-haptic units at low voltages by optimizing the electromechanical response characteristics of flexible materials.

3.3. Thermal feedback and multimodal fusion via thermoelectric actuation

Thermal feedback aims to simulate environmental temperature and the thermal conductivity of object materials, serving as a critical dimension for enhancing environmental immersion

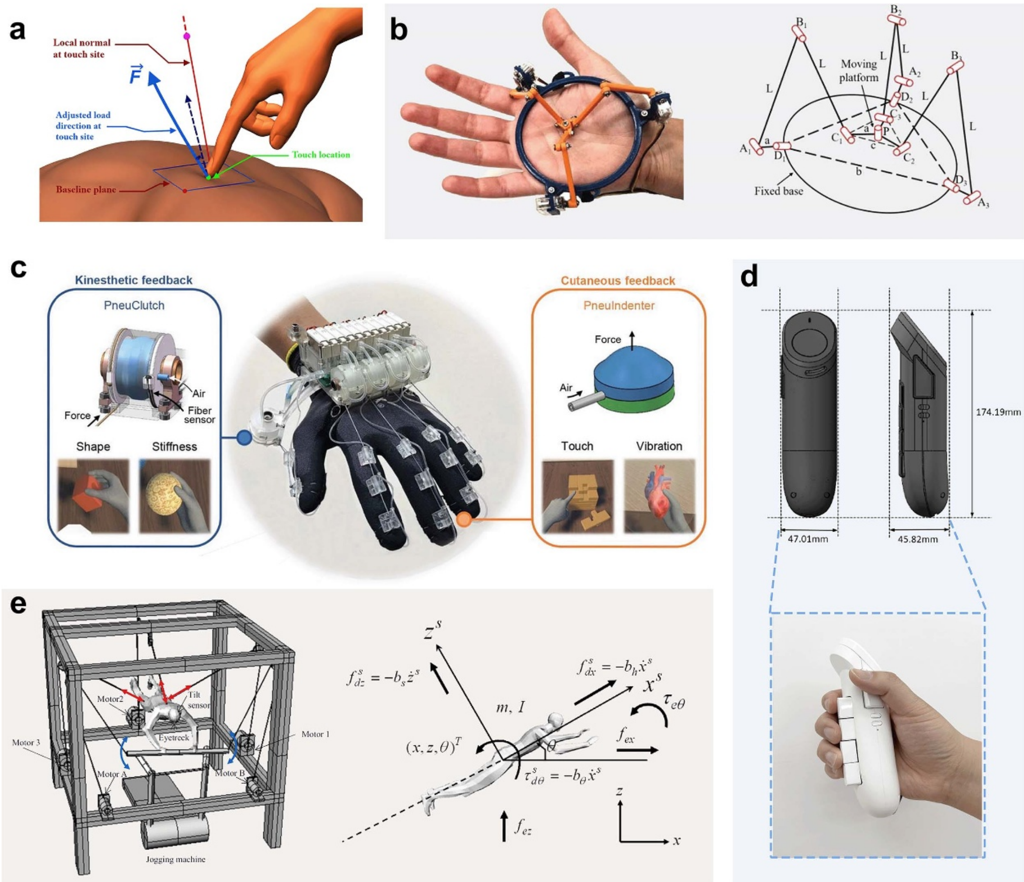

Figure 8. Kinesthetic feedback technologies tailored to enable immersive VR haptic interactions. (a) 3-RRR parallel mechanism-based force vector rendering. DeltaFinger derives corrected vectors from virtual object surface normals for 3D fingertip kinesthetic feedback. (b) Inverted Delta-structured DeltaTouch palm haptic device. The left shows the wearable hardware mounted on the palm; the right depicts its parallel kinematic architecture which enables 3D force vector delivery for VR weight and texture simulation. Reproduced with permission [37]. Copyright 2019, IEEE. (c) HaptGlove's dual-feedback modules. Center shows the wearable glove; Left (PneuClutch, kinesthetic) delivers object shape/stiffness via air and fiber sensor; Right (PneuIndenter, cutaneous) provides touch/vibration feedback for VR interactions. Reproduced with permission [78]. Copyright 2023, Wiley-VCH. (d) BStick handheld linear actuator for model diagram and dimensional information, as well as its physical device photograph (enclosed in the dashed frame). Reproduced with permission [79]. Copyright 2023, ACM. (e) Cable-controlled haptic motion simulator for VR flight. Integrating motors (1–3, A-B), tilt sensor, Eyetreck, joystick, and jogging machine, it synthesizes cable tension to deliver full-body gravity and acceleration feedback for hang gliding simulation. Reproduced with permission [38]. Copyright 2011, Cambridge University Press.

[88, 89]. Current Thermoelectric Actuation technology primarily relies on the Peltier effect. Moon and Chin [90] established a heat transfer model based on Newton's law of cooling, successfully simulating the thermal difference sensation between wood (low thermal conductivity) and metal (high thermal conductivity) at the moment of contact by precisely controlling the direction and magnitude of current in Peltier elements (figures 10(a) and (b)). However, thermal actuators often face challenges of large volume, high power consumption, and slow response (thermal inertia). Multimodal integration and illusion application have become the solution. Wang *et al* [91] utilized the thermal referral illusion, placing the heat source on the back of the finger while inducing a sensation of heat on the finger pad, effectively resolving the issue of wiring congestion at the fingertip (figure 10(c)). In terms of miniaturized integration, Nozawa *et al* [92] proposed a shape memory alloys (SMA)-Peltier Fusion Scheme, integrating the micro-vibration function of SMA with the heating/cooling regulation of Peltier elements within a tiny 20 mm^2 space (figure 10(d)). This compact, multi-modal integration design directly addresses the challenge of limited wearable space in VR/AR devices by resolving the volumetric conflict between different actuator modalities, enabling high-density, simultaneous delivery of temperature and vibration feedback without compromising ergonomics or wearing comfort, and is thus well-suited for both cutaneous sensation assessment in medical diagnosis and tactile feedback implementation in compact immersive VR/AR interaction devices.

3.4. Full-body interaction for immersion

While the manipulation of virtual objects relies heavily on manual dexterity, the sensation of presence within a large-scale virtual environment is fundamentally anchored in locomotion. Haptic interaction should therefore extend

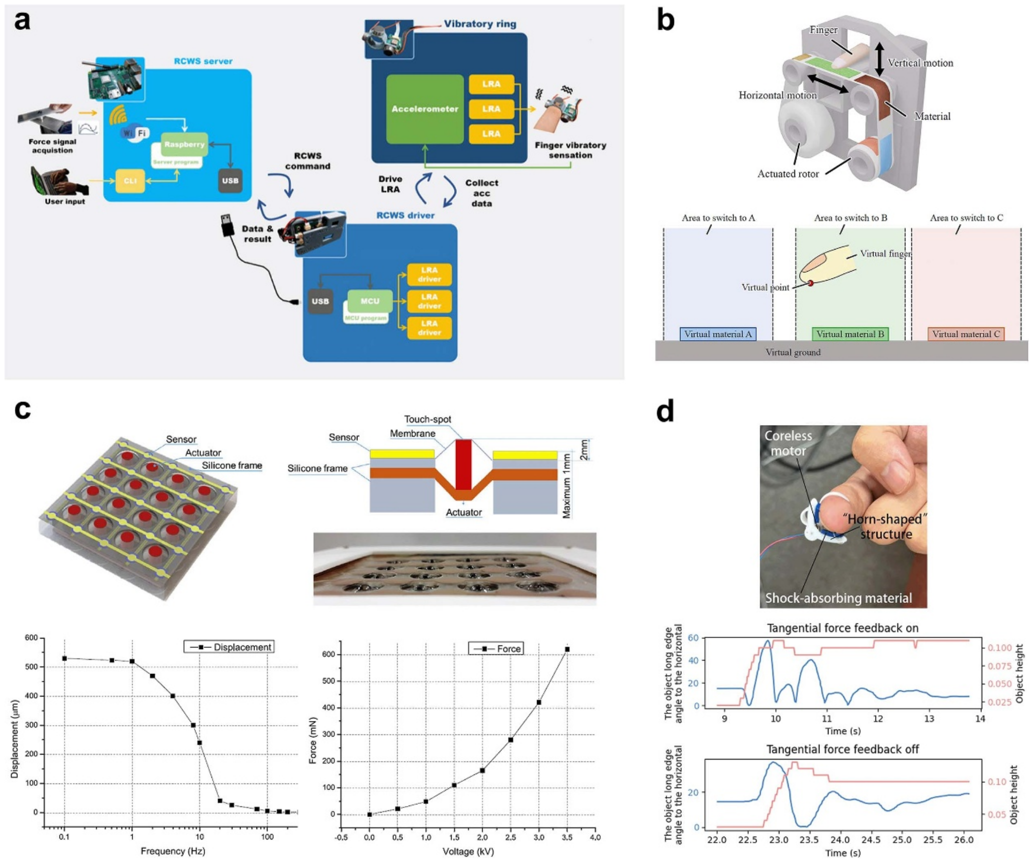

Figure 9. Cutaneous feedback technologies for mechanoreceptors simulation on the skin surface. (a) Data-driven vibrotactile rendering system architecture. Force signals are acquired from user interaction and processed by the RCWS server. The RCWS driver controls LRA arrays, which are mounted on a vibratory ring, to output vibration waveforms, delivering realistic texture feedback to the finger. Reproduced with permission [82]. Copyright 2023, MDPI. (b) MateREAL system's material reproduction mechanism. Top displays its rotor-driven physical structure for material motion. Bottom shows VR scene logic. Virtual finger interactions trigger dynamic switching of 30 real materials at the fingertip, eliminating vibration texture distortion. Reproduced with permission [84]. Copyright 2025, MDPI. (c) Dielectric elastomer-based soft actuator system. Integrated structure with soft tactile sensor and actuator array in a silicone frame. Actuator displacement-frequency response and force-voltage response show that sensor detects touch to trigger actuators, enabling up to 600 mN force output with fast response. Reproduced with permission [85]. Copyright 2021, IEEE. (d) Nail-mounted tangential force haptic device. Hardware includes coreless motor, horn-shaped structure and shock-absorbing material, stimulating fingernail sidewalls to simulate finger pad tangential forces. Graphs show more frequent fine adjustments by users with haptic feedback enabled (top) versus disabled (bottom), preserving bare-hand sensitivity via non-contact design. Reproduced with permission [86].

beyond the hands to the feet and body [90, 93]. In typical VR locomotion scenarios, the discrepancy between the visual perception of movement and the absence of physical ground reaction forces creates a vestibular–visual conflict, frequently triggering cybersickness and a sensation of floating [94]. To resolve this, haptic feedback systems are evolving to provide the full-body experiences. Fluidic Variable Stiffness Technology demonstrates unique advantages in reconstructing these ground reaction forces. Yang *et al* [95] developed the RealWalk insole, utilizing the viscosity change characteristics of magnetorheological (MR) Fluid under magnetic fields to real-time simulate the physical attributes of diverse terrains, such as snow (high damping), mud (viscous), and hard ground (figure 11(a)). Such fluid rheology-based feedback systems possess a broader adjustable compliance spectrum compared with conventional vibration motors, enabling accurate simulation of ground texture and mechanical impedance.

From a systemic perspective, latency compensation is essential to eliminate the intrinsic mechanical delay of large-scale haptic feedback equipment. de Tinguy *et al* [96] proposed a compensation strategy integrated with visual redirection (figure 11(b)), which leverages capacitive sensing to capture real-time proximity signals of the user's feet relative to the interaction surface, thereby accurately predicting foot placement trajectories. Simultaneously, it deploys subtle visual adjustments in the virtual scene to imperceptibly fine-tune the user's perceptual expectations of movement timing and spatial positioning. This synergistic mechanism, which fuses high-precision sensing data with imperceptible visual modulation, effectively masks the response lag of actuators, sustains the continuity of immersive experience during locomotion, and ensures the seamless integration of proprioceptive cues from body movement and visual cues from the virtual environment.

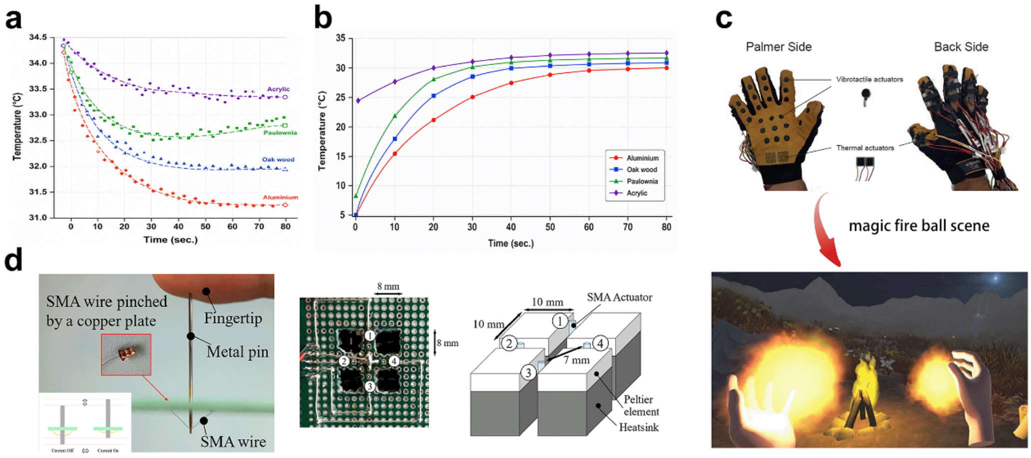

Figure 10. Thermoelectric actuation-based thermal feedback technologies. (a) The surface of the user's hand changes over time while touching Acrylic, oak, paulownia coreana and aluminum. (b) Surface temperature graph with time of vibration motor to express each material. (c) Referral illusion from thermal-tactile glove. Vibrotactile actuators are placed on the palmer side and thermal actuators on the finger back side. In the VR scene of interacting with a virtual fireball, the back-mounted thermal actuators activate, and via the thermal referral illusion, users perceive heat on the palm pad. Reproduced with permission [91]. Copyright 2024, IEEE. (d) Physical assembly (left), circuit board integration (middle) and structural diagram (right) of SMA-Peltier fusion actuator. SMA actuators (1,3) and Peltier elements (2,4) are arranged in a compact layout. SMA generates micro-vibration via current-controlled phase transitions, while Peltier regulates heating/cooling, resolving modal volumetric conflict to enable dual vibration-temperature high-density output. Reproduced with permission [92]. Copyright 2024, MDPI.

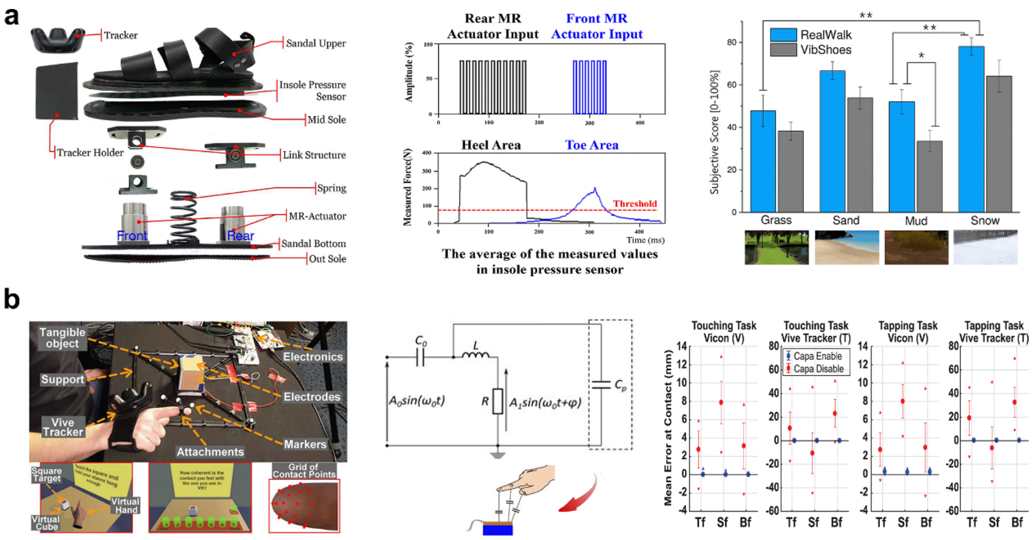

Figure 11. Haptic technologies for enhancing full-body VR immersion. (a) RealWalk haptic shoe system for simulating terrain-specific ground reaction forces. System schematic shows the sandal-integrated core hardware including MR actuators, pressure sensor and tracker. Curve plots insole pressure variation over time with activation threshold. Subjective realism ratings across four terrains versus vibrotactile shoes confirm enhanced ground attribute replication. Reproduced with permission [95]. Copyright 2021, IEEE. (b) Capacitive-optical fusion contact rendering system mitigates visuohaptic asynchrony. Capacitive sensing detects fingertip proximity to correct optical tracking errors, and RLC oscillator converts proximity into measurable signals. Error at contact/contact coherency scores across touching/tapping tasks with Vicon/Vive and three cube faces (Tf: top, Sf: side, Bf: back) reduce tracking mismatches to submillimeter levels. Reproduced with permission [96]. Copyright 2021, IEEE.

In summary, multimodal haptic feedback technology is navigating a critical transition from simple symbolic cueing to high-fidelity physical-level reproduction. Table 1 summarizes key mechanical and functional parameters of typical materials used in haptic sensing and actuation. However, the path toward widespread adoption is obstructed by distinct engineering gaps: the power-portability Paradox, where the bulky power requirements of high-fidelity exoskeletons contradict the lightweight imperatives of mobile VR; Multimodal Crosstalk, where integrating diverse actuation units within the confined space of a fingertip leads to mechanical wave coupling and heat accumulation; and response latency, particularly in thermal and pneumatic systems (often >100 ms), which significantly lags behind visual perception (<20 ms), shattering instantaneous immersion. Consequently, future haptic display technologies must inevitably evolve toward lightweight

Table 1. Summary of some key properties of representative materials and composites for VR/AR haptic sensing and feedback systems.

Material/Composite	Role	Young's modulus	Response time	Frequency range	Transduction modality	Skin compatibility	References
Polydimethylsiloxane (PDMS)	Sensing/actuation	360–870 kPa	<1 ms	<15 kHz	Piezoresistive, Capacitive, Fluidic Actuation	Excellent (biocompatible, widely used in wearable devices)	[97, 98]
Polyurethane foam (PUF)	Sensing	∼0.08 MPa	<30 ms	<100 Hz	Capacitive, Piezoresistive	Good (flexible, low irritation)	[99–101]
MBene/rGO/PUF Gradient composite	Sensing	Similar to PUF	<60 ms	<1.5 kHz	Capacitive	Excellent (ultra-flexible, conformal contact)	[48, 102]
Fe–Ga magnetostrictive Alloy	Sensing	∼70 GPa	<1 ms	<100 kHz	Magnetostrictive	Fair (rigid, requires packaging for wearables)	[64, 103, 104]
Silica Optical Micro/Nanofiber (MNF)	Sensing	∼72 GPa	<25 ms	<1.5 MHz	Optical (bending loss, interferometry)	Good (EMI-immune, corrosion-resistant)	[69, 105, 106]
Polyvinyl Alcohol (PVA) Conductive Hydrogel	Sensing	310–800 kPa	10–200 ms	<100 kHz	Piezoresistive, Capacitive, Ionic Conductive	Excellent (biocompatible, skin-conformal, no skin irritation)	[107–109]
NiTi-based Shape Memory Alloy (SMA)	Actuation	Austenite: 66.8 GPa, Martensite: 24.8 GPa	0.3–2 s	<10 Hz	Thermomechanical Actuation	Good (biocompatible, widely used in medical devices)	[110, 111]
Magnetorheological (MR) Fluid	Actuation	N/A	<4 ms	<300 Hz	Magnetorheological Actuation	Good (encapsulated, low irritation)	[95]
Eutectic Gallium-Indium (eGaIn) Liquid Metal	Sensing/interconnect	∼210 kPa	<400 ms	∼10 Hz	Piezoresistive, Capacitive	Excellent (non-toxic, high conductivity, stretchable)	[112–114]
Polyimide (PI) Flexible Substrate	Sensing/actuation Substrate	∼2.5 GPa	N/A	N/A	Substrate for all electrical/optical modalities	Excellent (biocompatible, widely used in flexible electronics)	[115, 116]
Lead zirconate Titanate (PZT) Piezoceramic	Sensing/actuation	50–70 GPa	<1 ms	<1 kHz	Piezoelectric	Fair (rigid, requires packaging for wearables)	[117, 118]
Silicone rubber (Ecoflex)	Sensing/actuation Substrate	8–40 kPa	<200 ms	∼5 Hz	Piezoresistive, Capacitive, Soft Actuation	Excellent (biocompatible, ultra-flexible)	[119, 120]
Polyvinylidene Fluoride (PVDF) Piezoelectric Film	Sensing/actuation	1.34–2 GPa	∼15 ms	0.1–1 kHz	Piezoelectric	Excellent (flexible, low toxicity)	[121–123]
Polyethylene Terephthalate (PET) Flexible Substrate	Sensing/actuation Substrate	∼5 GPa	N/A	N/A	Substrate for all electrical/optical modalities	Good (non-irritating, non-sensitizing)	[124, 125]

flexible materials, high-density micro-nano fabrication, and multiphysics synergy, providing a more efficient hardware carrier for intelligent system integration. Furthermore, to construct an interactive system truly possessing embodiment, one must bridge the gap from component stacking to system fusion.

4. Intelligent integrated systems

Isolated sensing materials or actuation devices cannot independently constitute an effective interaction loop; they must connect the physical world and digital space through system-level integration and intelligent processing. Figure 12 depicts the full framework of intelligent integrated tactile systems. From the loop's perspective, even perfectly digitalized contact data and perfectly reconstructed stimuli still produce a Ghost Hand experience if the processing layer fails to deliver them in time and in semantic alignment with the user's intent. Serving as the processing and integration center within the sensing-computing-feedback logical chain, it addresses two core challenges: Physical Integration, organizing dispersed sensors and actuators into ergonomic wearable forms like data gloves or e-skins; and intelligent parsing, utilizing AI algorithms to translate raw analog signals into semantic digital commands. The following discussion progresses from foundational integration to advanced intelligence, beginning with an examination of system-level integration architectures from wearables to bio-integrated interfaces that tackle the physical integration challenge. Next, we delve into algorithmic architectures for spatial feature extraction and time-series modeling, focusing on the intelligent parsing challenge. Emerging in-sensor computing and edge inference paradigms are finally explored, which embody the synergistic fusion of these two pillars to enable next-generation intelligent tactile systems. This stage represents the critical hub for the transition from passive signal acquisition to active intelligent cognition, providing the edge-intelligent hardware carrier for complex applications.

4.1. System-level integration architectures from wearables to bio-integrated interfaces

Effective haptic systems require more than just high-performance components; they demand architectural strategies to seamlessly unite sensing, actuation, and processing units into a cohesive whole [131]. Current integration approaches generally follow two distinct system-level paradigms, including functional wearable architectures for immersive feedback and bio-integrated conformal architectures for invisible monitoring [132, 133]. On the one hand, resolving mechanical and electrical complexity the primary challenge in wearable systems lies in integrating rigid actuators and dense sensor arrays without compromising ergonomic compliance. Moving beyond simple component stacking, Sarkar *et al* [134] demonstrated a hybrid system architecture that fuses soft pneumatic/motor feedback with carbon-based sensors (figure 13(a)). This design achieves synergistic proprioception and kinesthetic feedback within a unified soft glove framework, resolving the dexterity limitations of traditional rigid systems. However, scaling these systems introduces severe wiring clutter, where the number of interconnects creates a bottleneck for lightweight integration. Pan *et al* [135] addressed this not through device innovation, but via a matrix addressing architecture using MOSFET-based traversal polling (figure 13(b)). This time-division multiplexing strategy significantly reduces interconnect density, enabling high spatiotemporal resolution with minimal circuit complexity. Furthermore, the interface between soft sensing materials and rigid control electronics represents a critical system failure point. Oh *et al* [114] utilized liquid metal (eGaIn) interconnects to engineer a fully soft-integrated interface, ensuring signal stability across the entire system during dynamic stretching (figure 13(c)). Scaling from hand to full-body systems, Serizawa *et al* [136] replaced discrete wiring with two-dimensional communication fabrics, establishing a body-area network that supports full-body immersive experiences without physical tethering. On the other hand, multilayer and imperceptible design distinct from the add-on nature of wearables, bio-integrated architectures aim to eliminate the mechanical boundary between the system and the skin. The focus here shifts to structural integration to achieve 'imperceptibility.' Wang *et al* [129] developed a substrate-free Au nanomesh (AuNM) system architecture that forms tight conformal contact with micron-scale skin features (figure 13(d)). Leveraging ultra-thinness and structural transparency instead of forceful clamping, it ensures high-fidelity strain and motion signal acquisition. To achieve system-level multifunctionality within such ultrathin form factors, Zhao *et al* [137] proposed a layered integrated architecture, enabling the synchronous decoupling of pressure, temperature, and material recognition within a single compact integrated unit (figure 13(e)). Addressing the system's mechanical integrity under deformation, Guo *et al* [138] implemented morphed serpentine trace architectures to adapt to the shape of magnetic actuators (figure 13(f)). This design maintains unobstructed actuator motion during tactile interaction while preserving structural stability, effectively optimizing the compact layout and boosting the tactile device's spatial resolution. Finally, introducing resilience into the system design, He *et al* [139] developed a self-healing modular architecture, allowing the system to physically recover functionality after damage and enabling user-reconfigurable layouts for diverse tasks.

4.2. Algorithmic architectures for spatial feature extraction and time-series modeling

With the surge in sensor array density, tactile data processing faces immense challenges. Traditional linear regression algorithms struggle to cope with the inherent nonlinearity, hysteresis, and high-dimensional features of flexible sensors, making deep learning-based intelligent algorithms the core driver [140, 141]. For pressure images generated by high-density tactile arrays, convolutional neural networks (CNNs) excel in extracting spatial features. Ouyang *et al* [128] utilized a five-layer CNN model to process pressure data from a 32×32 pixel

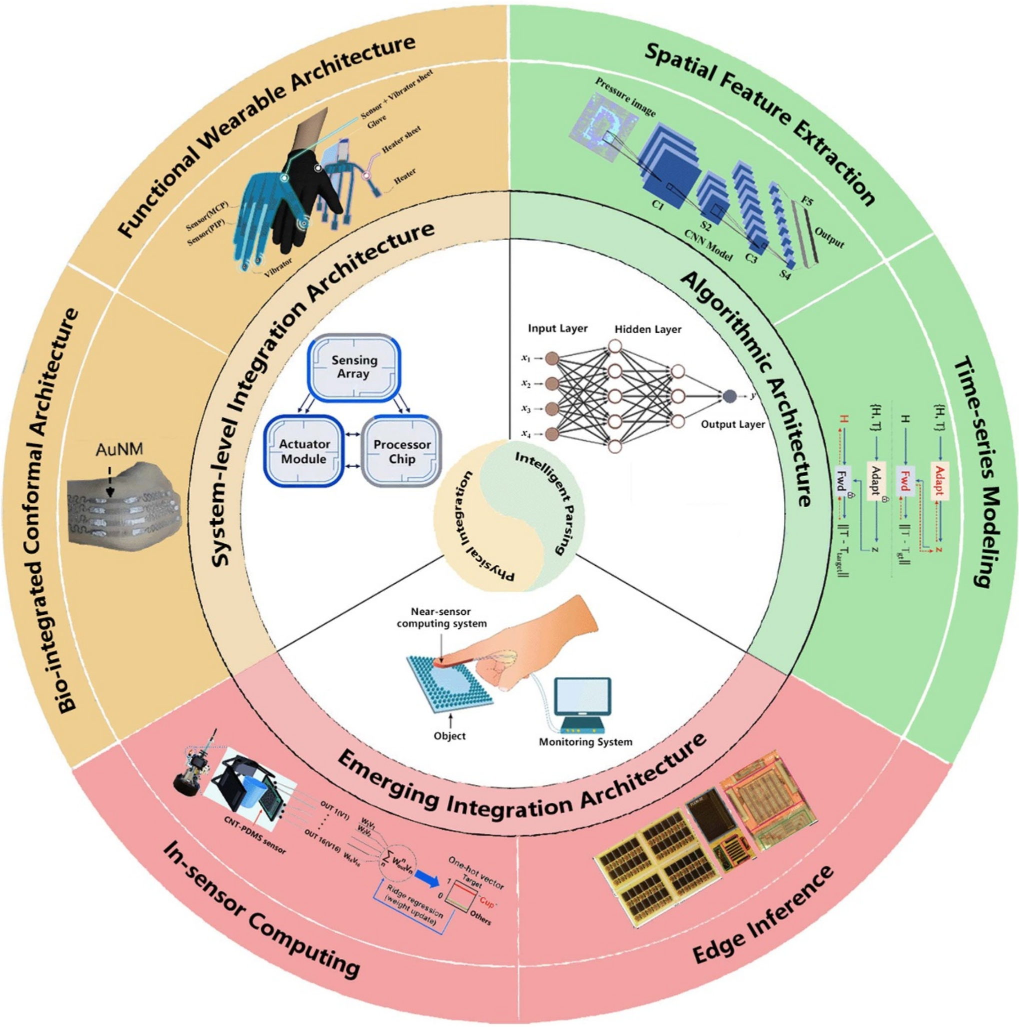

Figure 12. Overview of intelligent integrated systems for tactile interaction with architectures for physical integration and intelligent parsing. Reproduced with permission [40]. Copyright 2022, Wiley-VCH. Adapted with permission [126]. Copyright 2024, Darcy & Roy Press. Reproduced with permission [127]. Copyright 2024, Springer Nature. Adapted with permission [128]. Copyright 2024, ACS. Adapted with permission [114]. Copyright 2020, Wiley-VCH. Reproduced with permission [129]. Copyright 2020, Elsevier. Reproduced with permission [130]. Copyright 2025, Wiley-VCH. Reproduced with permission [39]. Copyright 2025, Springer Nature.

array, achieving 96.1% accuracy in recognizing complex curvilinear patterns, significantly surpassing human fingertip discrimination (figure 14(a)). In material perception, Wu *et al* [142] employed a 1D-CNN to process hybrid e-skin signals, realizing high-precision classification of different textures (figure 14(b)). To tackle complex noise interference in practical applications, Zhang *et al* [143] proposed RobustVisH, an enhanced cross-modal feature extraction and fusion network that significantly improves recognition robustness under low SNR conditions (figure 14(c)). Furthermore, multi-modal signal fusion is key to enhancing contextual interaction precision. Yu *et al* [144] developed a hyperconformal metaskin capable of simultaneously capturing proprioceptive skin stretch and tactile localization signals (figure 14(d)). By leveraging complementary somatosensory information, this approach drastically improved the adaptability of contextual interaction tasks, demonstrating the superiority of multi-source somatosensory fusion in complex human-machine interactions.

Besides, tactile signals are inherently time-variant sequences. Addressing this strong temporal correlation, Transformer architectures have been introduced to capture long-range dependencies. Lee *et al* [145] proposed a Self-Teaching Vision Transformer using self-distillation technology, achieving precise classification of walking gestures on carpet-based tactile sensors, showcasing the potential of attention mechanisms in processing large-scale spatiotemporal tactile data (figure 14(e)). Meanwhile, considering the computational constraints of wearables, Burrello *et al* [146] explored the application of lightweight Bioformer, a Transformer-based architecture, on resource-constrained devices, proving effective extraction of complex temporal features while reducing computational overhead (figure 14(f)). The core of intelligent systems lies not only in recognition but also in adaptation to user behavior. Due to individual differences (e.g. hand shape, force habits), tactile feedback parameters often require tedious calibration. Luo *et al* [127] introduced a few-shot adaptive

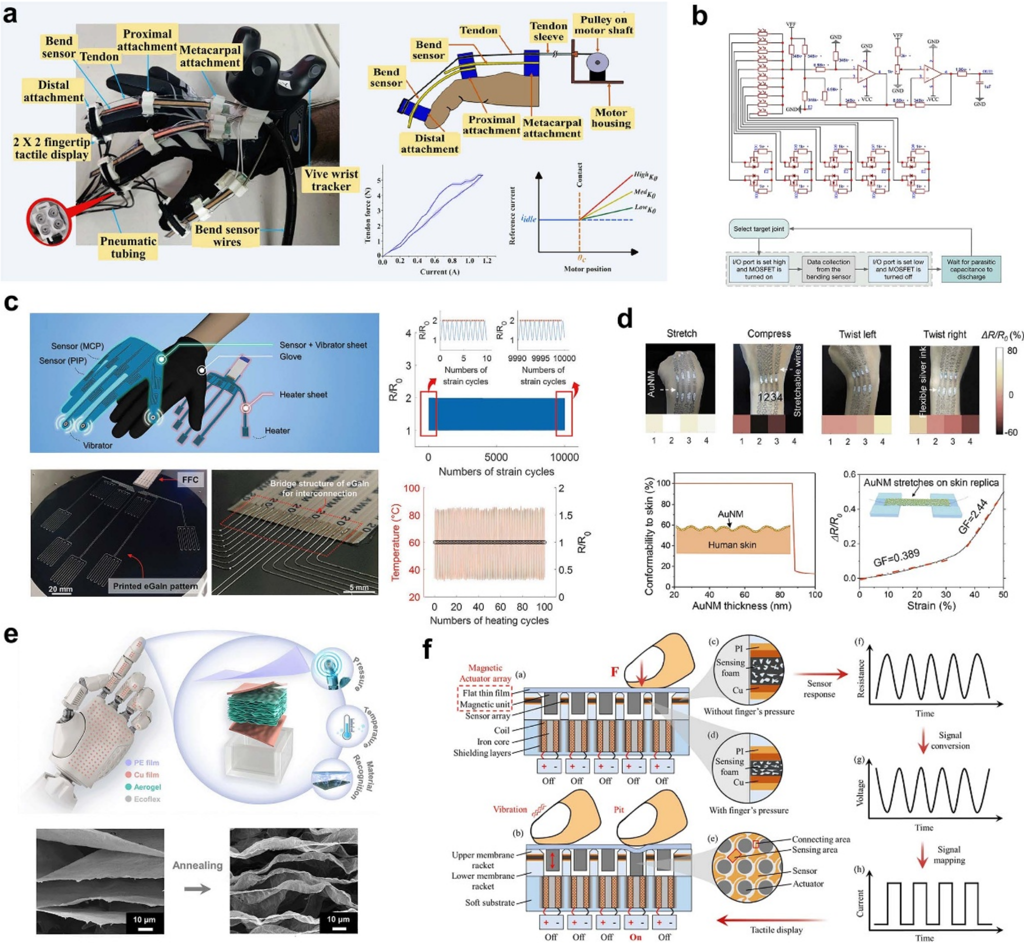

Figure 13. System-level integration architectures for haptics. (a) Photograph and schematic of the integrated soft VR glove system with assembled sensing/feedback modules, and the motor-tendon kinesthetic feedback arrangement. Included are diagrams show the characteristics plot of the motor-tendon system and reference current computation scheme for different feedback stiffness during virtual object manipulation. Reproduced with permission [134]. Copyright 2025, Springer Nature. (b) Circuit diagram of the MOSFET-based multi-channel traversal polling architecture and schematic of the traversing cyclic collection process. Reproduced with permission [135]. Copyright 2024, Wiley-VCH. (c) Micrographs of patterned eGaIn on a coated silicone layer and eGaIn bridge structures connecting patterned eGaIn to FFC. Diagrams show resistance changes during 10 000 cyclic strain tests (50% strain, 20 mm s^{-1}) and cyclic heating tests, demonstrating signal stability across dynamic stretching and heating. Reproduced with permission [114]. Copyright 2020, Wiley-VCH. (d) Thermal images of AuNM ribbons under stretching (17.9%–28.6% strain), compression (−28.6% to −21.4% strain), and twisting (left: −7.1% to 14.3% strain; right: −28.6% to 7.1% strain), with a plot of conformability versus AuNM thickness, and a graph of resistance change versus strain for AuNM on skin-textured PDMS. The substrate-free Au nanomesh forms tight conformal contact with skin features through ultra-thinness, enabling high-fidelity strain and motion signal acquisition. Reproduced with permission [129]. Copyright 2020, Elsevier. (e) Schematic of the MTAS hierarchical layered architecture and its SEM images of the ordered nano-layered carbon aerogel, realizing ultrathin stacked design for multi-signal sensing recognition. Reproduced with permission [137]. Copyright 2023, Springer Nature. (f) Schematic of the reticular layout of magnetic actuators and piezoresistive sensors with morphed serpentine traces, alongside diagrams illustrating actuator motion (vibration/pit formation) and sensor resistance changes under finger pressure, exhibiting unobstructed motion and high resolution. Reproduced with permission [138]. Copyright 2024, IEEE.

machine learning module, enabling smart gloves to automatically optimize feedback parameters based on real-time user reactions, realizing rapid personalized system calibration (figure 14(g)). Combined with the active exploration strategy proposed by Drimus *et al* [147], the system can acquire temporal tactile information through dynamic palpation actions, utilizing dynamic time warping algorithms to distinguish rigid and soft objects, simulating the cognitive process of human active touch (figure 14(h)).

4.3. Emerging in-sensor computing and edge inference

The traditional acquire-transmit-cloud process model faces bottlenecks of high latency and bandwidth consumption in VR interactions. To achieve real-time feedback, the computational paradigm is migrating toward the near-sensor edge [148, 149]. In-sensor computing aims to process signals directly at the physical level, reducing power consumption associated with analog-to-digital conversion (ADC) and data transmission

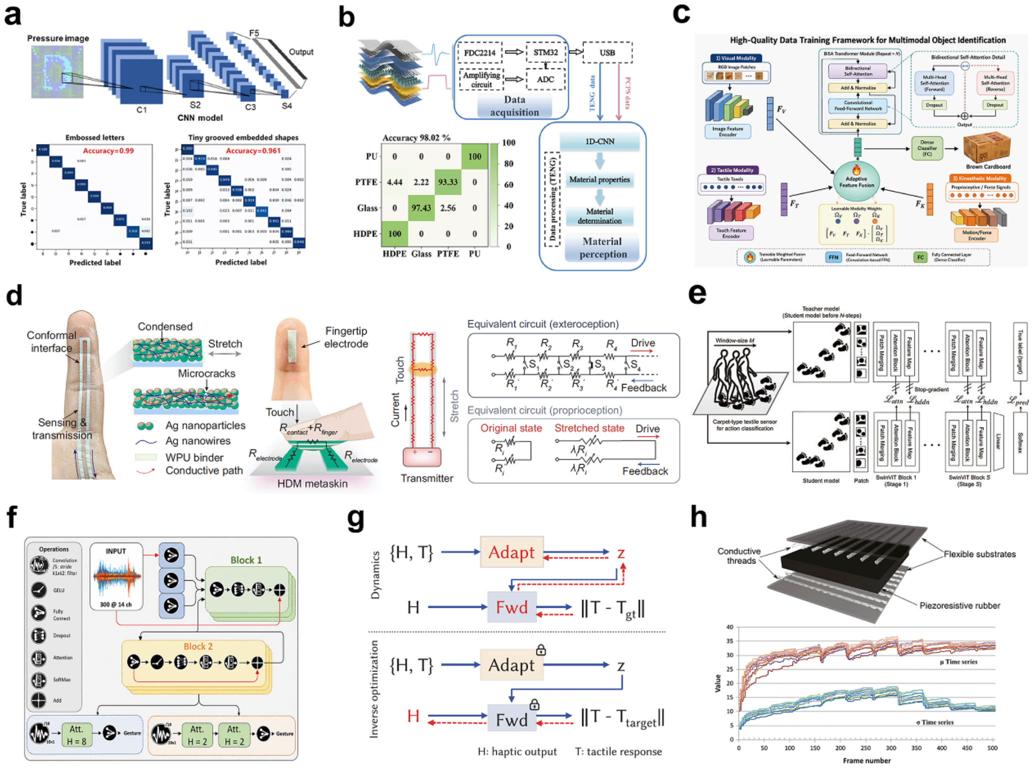

Figure 14. Algorithmic architectures for spatial feature extraction and time-series modeling in haptics. (a) Schematic of the five-layer CNN model (2 convolution layers, 2 pooling layers, 1 fully connected layer) for processing pressure images, alongside confusion matrices of the CNN classifying pressure image maps from embossed letters (accuracy = 0.99) and tiny grooved embedded shapes (accuracy = 0.961). Adapted with permission [128]. Copyright 2024, ACS. (b) Workflow of the multi-information recognition HCI system based on the hybrid e-skin (TPES). The confusion matrix illustrates the perception accuracy of 98.02% for four materials, achieved using the trained 1D-CNN model. Reproduced with permission [142]. Copyright 2024, Elsevier. (c) Schematic of the RobustVisH network architecture, featuring modality-specific 1D feature encoding, Trainable Weighted Fusion (TWF), and BiSA-Transformer (BiSAT) for cross-modal feature extraction and fusion. (d) Schematic of the hyperconformal dual-modal (HDM) metaskin conformally attached to fingers, and equivalent circuits for exteroceptive tactile localization and proprioceptive skin stretch sensing modes. Reproduced with permission [144]. Copyright 2025, Springer Nature. (e) Architecture of the Self-Teaching Vision Transformer (STViT), integrating self-distillation technology and patch merging for processing spatiotemporal tactile data from carpet-based sensors. Reproduced with permission [145]. Copyright 2023, IEEE. (f) Schematic of the lightweight Bioformer architecture, including the basic multi-head self-attention (MHSA) layer and two benchmark Transformer-based architectures tailored for resource-constrained wearable devices. (g) Overview of the human model learning and inverse haptics optimization pipeline, incorporating a forward dynamics model with a few-shot adaptive module, vibrotactile haptic output (H) and tactile response (T). Reproduced with permission [127]. Copyright 2024, Springer Nature. (h) Structure of the flexible piezoresistive tactile sensor and time series graphs of μ and σ describing the palpation procedure of the full bottle object. The setup enables the acquisition of temporal tactile information through dynamic palpation, supporting the distinction between rigid and soft objects via dynamic time warping Reproduced with permission [147]. Copyright 2012, Elsevier.

[150]. Kimizuka *et al* [130] utilized the nonlinear physical characteristics of CNT/PDMS nanocomposites to construct a reservoir computing architecture (figure 15(a)). This system performs feature mapping and processing of tactile signals directly in the analog domain, significantly lowering system power consumption and enhancing response speed, providing the physical basis for zero-latency tactile feedback. At the digital processing level, edge computing offloads inference tasks to the local wearable device. Pan *et al* [151] demonstrated a microcontroller-based edge machine learning solution, deploying multi-channel capacitive-sensing gesture classification algorithms locally on the glove, effectively reducing reliance on wireless transmission bandwidth (figure 15(b)). Building on this, Yan *et al* [39] proposed the FLEXI flexible digital CIM edge inference accelerator with hardware-software co-optimization (figure 15(c)). By adopting a customized reconfigurable CIM hardware architecture, it further cuts the energy consumption of complex algorithms on wearables, laying the foundation for building low-latency, long-endurance intelligent tactile systems. Moreover, recent breakthroughs have established a new paradigm for integrated sensing-memory-computing toward VR/AR. Wei *et al* [152] proposed an octopus-inspired tactile sensor with in-sensor computing, enabling ultrafast edge intention recognition and breaking the bottleneck of conventional separated architectures. Liu *et al* [153] further developed a sensing-memory-logic unified device using reversible filament networks, achieving high-precision motion recognition with ultra-low latency. By merging sensing, memory, and computing at the hardware level, these works fundamentally eliminate latency from signal conversion and transmission. This greatly boosts the real-time performance and immersion of VR/AR

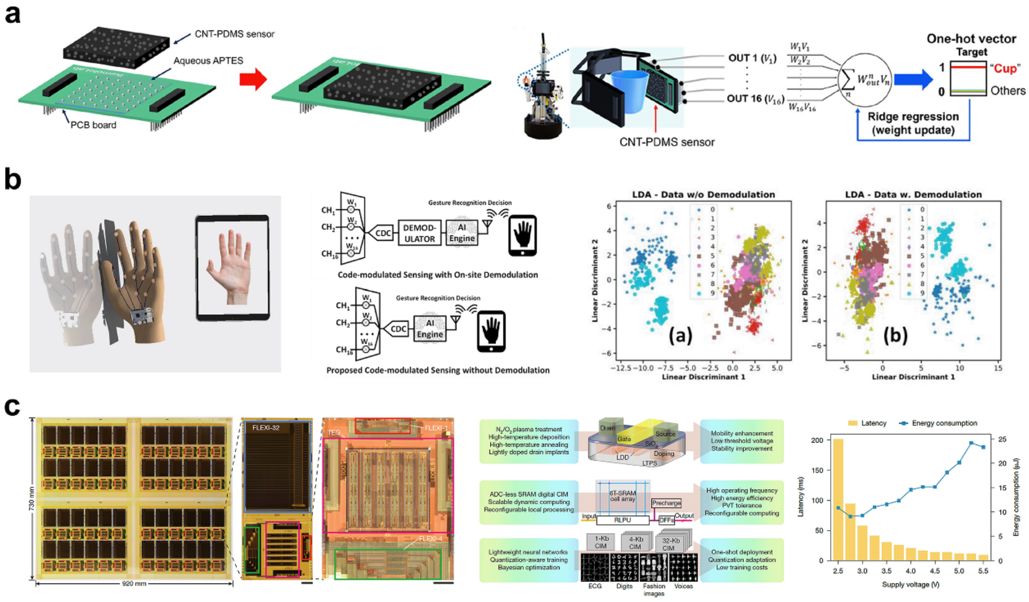

Figure 15. Emerging in-sensor computing and edge inference paradigms for intelligent tactile systems. (a) Schematic illustration of the CNT-PDMS sensor attached to a printed circuit board. Object classification is based on dynamic tactile signal processing via reservoir computing architecture with linear regression for weight update and one-hot vector output, realizing analog-domain tactile signal feature mapping and processing. Reproduced with permission [130]. Copyright 2025, Wiley-VCH. (b) Illustration of the wearable gesture-recognition smart glove prototype with multi-channel capacitive sensors. Comparisons were shown regarding wireless multi-channel sensing solutions between code-modulated with on-site demodulation and the demodulation-free scheme, and linear discriminant analysis of code-modulated capacitive data with and without demodulation for gesture recognition. Reproduced with permission [151]. Copyright 2020, IEEE. (c) Overview of the FLEXI flexible digital compute-in-memory (CIM) chip family (FLEXI-1, FLEXI-4, FLEXI-32) fabricated on a GEN-4.5 LTPS-TFT panel, with micrographs of individual chips and a test element group (TEG). The cross-level co-optimization (CLCO) across fabrication process, circuit and algorithm levels for FLEXI is hierarchical presented. Latency and energy consumption of FLEXI-1 test results was shown for on-chip multiplication during routine activity classification under different supply voltages. Reproduced with permission [39]. Copyright 2025, Springer Nature.

haptic interactions in the future, establishing a key technical route for compact, low-power intelligent interactive systems.

The device development in flexible electronics and the algorithmic empowerment of deep learning have successfully constructed an intelligent integrated system possessing full-link sensing-computing-feedback capabilities, solving the engineering challenges from signal acquisition to intent understanding. However, the construction of this technical closed loop is not the endpoint; its core value ultimately depends on performance validation in complex real-world environments.

5. Scenario-driven validation

The transition of haptic technology from laboratory prototypes to practical adoption is driven by critical functional demands across diverse vertical sectors, where visual and auditory feedback alone are no longer sufficient to meet the requirements of safety, efficacy, and immersion. Figure 16 showcases all representative application scenarios of haptic interaction. Each scenario below is selected because the Ghost Hand bottleneck takes a distinctively different form there—force transparency in teleoperation, neural re-mapping in rehabilitation, material tangibility in digital artistry, sensory augmentation in extreme environments, and emotional embodiment in entertainment.

5.1. Robotic teleoperation and digital twins

This scenario primarily draws on the magnetic/optical force decoupling sensors of sections 2.2 and 2.3, the rigid-parallel kinesthetic actuation of section 3.1, and the low-latency edge inference of section 4.3, since the operator must feel sub-Newton contact transients within a closed control loop. In scenarios such as hazardous environment operations or microsurgery, operators face severe visual limitations, including latency, occlusion, and loss of depth perception [159–161]. Haptic technology aims to reconstruct the mechanical loop, achieving force transparency where the operator feels as if they are directly interacting with the remote environment [162, 163]. Targeting the classic challenge of grasping fragile objects, Wu *et al* [164] demonstrated the decisive role of tactile feedback within the tele-MPPI framework (figure 17(a)). By combining VR tracking with real-time haptic feedback, the system allowed operators to perceive millisecond-level contact force changes. Experiments showed that for fragile items like strawberries, haptic feedback enabled dynamic strategy adjustment, significantly reducing damage rates compared to vision-only control. This mechanism transcends simple force transmission; it enables predictive contact management via algorithmic assistance. In unstructured aerial tasks, visual instability exacerbates operational difficulty. Yashin *et al* [155] developed the AeroVR system, utilizing haptic gloves to assist drone arm manipulation (figure 17(b)).

Figure 16. Broad interaction scenarios driving the validation of haptic technologies from laboratory to practice. Adapted with permission [154]. Copyright 2024, Wiley-VCH. Adapted with permission [155]. Copyright 2019, IEEE. Adapted with permission [41]. Copyright 2019, Springer Nature. Adapted with permission [156]. Copyright 2017, Elsevier. Adapted with permission [14]. Copyright 2019, Springer Nature. Reproduced with permission [157]. Copyright 2021, IEEE. Reproduced with permission [158]. Copyright 2020, Springer Nature.

Research indicated that during unstable hovering, vision-only operation resulted in high error rates. However, the introduction of vibrotactile feedback allowed operators to perceive grasping states and limit warnings through their hands, effectively compensating for visual jitter and information loss. Addressing the high cost of high-fidelity force feedback, Pelliccia *et al* [156] explored a low-cost alternative: tactile visualization (figure 17(c)). By mapping fingertip pressure distributions from tactile arrays into visual heatmaps within a digital twin, this approach converts invisible force into visible data. Comparative analysis revealed that while lacking the immersion of direct force feedback, this method offers unique advantages in global monitoring and pressure distribution interpretation, providing a pathway for cost-effective teleoperation.

5.2. Medical rehabilitation and education

Medicine represents the domain where haptics has achieved the deepest validation. Its core mechanism leverages haptic feedback to activate the somatosensory cortex, promoting neuroplasticity and muscle memory. The dominant technology coupling here is between vibrotactile cutaneous feedback (section 3.2), temporally aligned multimodal fusion (section 3.4), and adaptive time-series learning (section 4.2) to drive neuroplasticity. Therapy haptics plays a unique role in rewiring erroneous neural circuits [165, 166]. Henriksen *et al* [167] designed a VR mirror therapy system that constructs a 'Visuo-Tactile Illusion' by mapping electrical stimulation from the healthy limb to the virtual avatar of the missing limb (figure 18(a)). This multimodal stimulation successfully 'tricks' the brain, restoring a sense of control over the phantom limb and significantly alleviating pain. This outcome validates the irreplaceable psychophysiological regulatory role of haptic feedback in neurorehabilitation. In stroke rehabilitation, haptics guides correct motor trajectories. Sadihov *et al* [168] utilized the 'Tactile Apparent Movement' phenomenon, generating directional tactile flows via glove vibration arrays to guide upper limb extension (figure 18(b)). Guo and Song [169] introduced force feedback devices (phantom omni) to

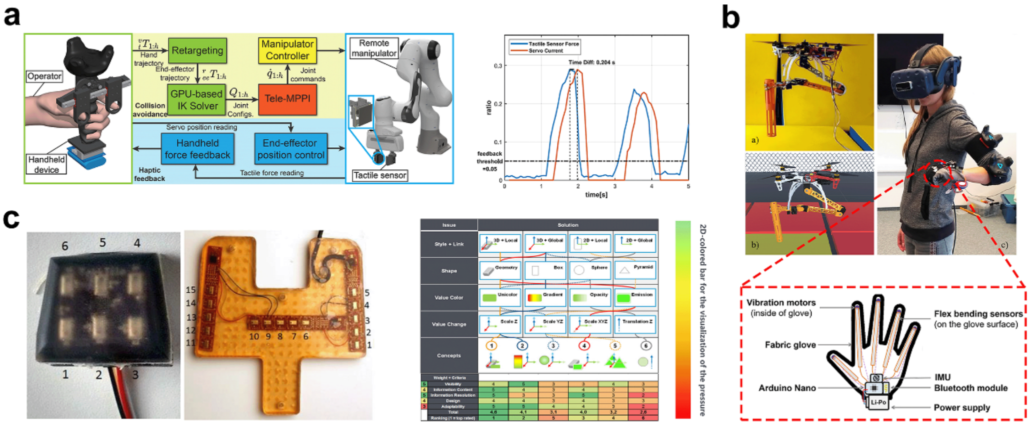

Figure 17. Overview of haptic teleoperation and digital twin strategies for robotic and aerial manipulation. (a) Overview of the VR-based robotic teleoperation system integrating haptic feedback and adaptive collision avoidance via the Tele-MPPI framework. The diagram shows haptic feedback latency performance of the system, with a time difference of 0.204 s between tactile sensor force detection and servo current response. Reproduced with permission [164]. Copyright 2025, IEEE. (b) Flight test of aerial manipulation, with the scheme of the smart haptic glove that detects finger flexion to control gripper motion, uses vibration to indicate object contact, and tracks hand orientation for joint adjustment, supplementing unstable visual feedback. Adapted with permission [155]. Copyright 2019, IEEE. (c) Fingertip and palm tactile arrays based on barometric sensors and benchmarking of pressure value visualization concepts. This tactile visualization approach maps fingertip pressure distributions into visible visual data, converting invisible force into intuitive visual feedback. Adapted with permission [156]. Copyright 2017, Elsevier.

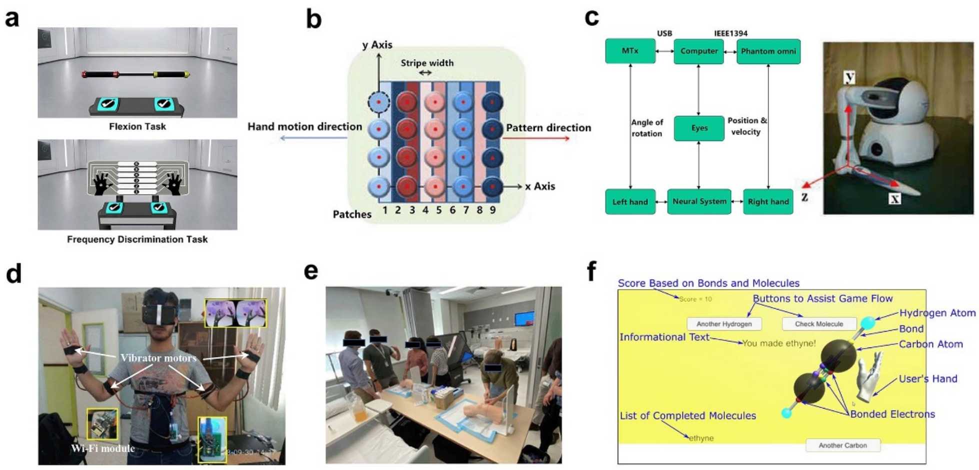

Figure 18. Multimodal haptic systems for medical rehabilitation and education. (a) Visualization of two VR games (bending game and frequency discrimination game) in the mirror therapy system, which maps the movement of the healthy limb to the virtual avatar of the missing limb and delivers tactile feedback via electrical stimulation on the stump. (b) Schematic of haptic grid patches (positions 1–9) used to generate directional tactile flows via glove vibration arrays. Reproduced with permission [168]. Copyright 2013, IEEE. (c) Schematic diagram of the VR-based upper limb rehabilitation system, alongside the system's virtual force model (including λ-model for strength augmentation and γ-model for simulating curving route boundaries). Adapted with permission [169]. Copyright 2008, IEEE. (d) Photograph of a user equipped with the low-cost haptic feedback system kit, which supports virtual training combined with haptics to improve hand-eye coordination and fine motor control. Reproduced with permission [170]. Copyright 2018, ACM. (e) Photograph of students using haptic gloves for knee puncture training in the hands-on practice station. Reproduced with permission [172]. Copyright 2024, Springer Nature. (f) Screenshot of the VR multisensory classroom (VRMC) displaying the triply-bonded ethyne molecule, with virtual control buttons to assist in molecule creation and guidance. Reproduced with permission [41]. Copyright 2019, Springer Nature.

construct virtual force fields, enabling an active rehabilitation mode where the healthy side drives the affected side (figure 18(c)). Quantitative studies by Benbelkacem *et al* [170] confirmed that virtual training combined with haptics significantly improved hand-eye coordination and fine motor control metrics compared to traditional therapy. Besides, in surgical training, haptics realizes the qualitative leap from seeing to doing (figure 18(d)). Controlled experiments by Maraza–Quispe and Palo–Rosas [171] and Singh *et al* [172] demonstrated that students using high-fidelity haptic gloves for suturing and knee puncture training significantly outperformed traditional model groups in precision and execution time (effect size η^2 up to 0.86) (figure 18(e)). Furthermore, systems like Edwards *et al*'s [41] VRMC allowed students to touch molecular structures, converting abstract chemical bond mechanics into intuitive force feedback, drastically reducing cognitive load (figure 18(f)).

5.3. Immersive art and design

In the realm of digital creativity, the absence of tactile feedback has long reduced 3D modeling and virtual painting to purely visual tasks, severing the artist's physical connection to their medium. Haptic technology is redefining this paradigm by restoring the tangibility of digital assets, enabling a shift from air gestures to physical crafting [145]. This use case relies on fluidic kinesthetic actuators (section 3.1) to render variable damping, paired with multimodal vibrotactile-thermal feedback (sections 3.2–3.3) for atmospheric immersion. Among these, precise force control is the soul of sculpting. Nam and Kwon [173] developed a specialized five-finger haptic controller utilizing linear actuators to simulate the variable damping forces encountered during spraying and carving (figure 19(a)). This system allows artists to physically perceive the density of virtual clay or the viscosity of paint, filling the gap in fine motor control for digital artistry and endowing digital creation with the texture of physical art. Beyond object manipulation, haptics enhances the atmospheric immersion of spatial design. Mochizuki *et al* [174] explored the fusion of vibrotactile and thermal feedback to simulate environmental elements. By rendering the sensation of wind flow and temperature gradients, designers can create sensory landscapes where users feel the dynamic of gusts or the warmth of sunlight (figure 19(b)). This expands the palette of artistic expression from audio-visual limits to a full-sensory spectrum, enabling the creation of emotionally resonant immersive installations.

5.4. Extreme environments and mission-critical operations

Beyond general industrial and medical applications, haptic technology plays an irreplaceable role in extreme environments, such as outer space, deep ocean, and disaster relief sites where visual and auditory channels are often compromised or unavailable [175]. The key technological coupling is between distributed e-textile sensing arrays (section 2.4 readout strategies) and vibrotactile/spatial encoding actuators (section 3.2), both of which must operate in the absence of reliable visual channels. In these mission-critical scenarios, haptics serves not merely as an interaction channel but as a vital survival mechanism for sensory augmentation and environmental perception. For example, in extravehicular activity (EVA), astronauts face the dual challenges of sensory deprivation caused by pressurized spacesuit gloves and spatial disorientation induced by microgravity. Payra *et al* [157] developed a haptic feedback system with exterior-integrated e-textile sensors for EVA suits (figure 20(a)). By utilizing multimodal e-textile sensors and haptic actuators to transduce environmental sensory data to the astronaut's skin, the system restored tactile sensitivity lost to thick pressurized layers, greatly boosting situational awareness and operational safety in space exploration. Furthermore, addressing the loss of vestibular cues in zero-gravity, van Erp *et al* [176] proposed a vibrotactile vest that continuously renders a gravity vector on the user's torso (figure 20(b)). This artificial proprioceptive cue helps astronauts maintain spatial orientation, effectively mitigating space motion sickness. In deep-sea operations or smoky rescue sites, visibility is often near zero. Camacho *et al* [177] introduced a vibrotactile torso system, encoding situational awareness cues into vibration patterns on a diver's torso to enable navigation in turbid water (figure 20(c)). Similarly, Stephanidis *et al* [158] demonstrated a Tactile Language System for firefighters via a haptic helmet, encoding commands (e.g. evacuate) into specific vibration patterns, ensuring 95% communication accuracy in high-noise, zero-visibility environments (figure 20(d)).

5.5. Interactive entertainment

While industrial and medical applications prioritize precision and function, the gaming and entertainment sector serves as the vanguard for consumer-grade haptics, driving the pursuit of hyper-realism and affective engagement [178, 179]. This scenario integrates consumer-grade vibrotactile and adaptive-resistance actuators (sections 3.1 and 3.2) with physiological-arousal coupling pipelines (section 4.2) to deliver affective rather than precision-driven haptics. Here, haptic technology transforms passive audio-visual storytelling into an embodied experience. In action genres, emotional immersion relies on amplifying arousal during intense moments. Kosuge *et al* [180] evaluated a haptic vest with thoracoabdominal vibrotactile actuators. By triggering real-time vibratory feedback in response to elevated skin conductance, a physiological marker of emotional arousal, the device amplifies feelings of excitement and frustration, significantly enhancing subjective emotional engagement and immersive arousal (figure 21(a)). Adaptive trigger technologies [181] further simulate variable mechanical resistance based on virtual object weight, reinforcing kinesthetic realism of virtual grasping (figure 21(b)). Haptics also conveys social subtext. Kirchner *et al* [182] demonstrated algorithms capable of synthesizing complex affective touch patterns, such as caressing strokes or gentle taps—through wideband actuators (figure 21(c)). This application of affective haptics fosters a deeper emotional connection, while studies on peripersonal space in immersive VR [183] suggest that even low-fidelity haptic feedback significantly increases threat sensitivity and expands the boundaries of personal space during social interactions (figure 21(d)).

Although the empirical studies across these diverse fields have validated the 'Sensing-Computing-Feedback' loop, these systems remain constrained by rigid structures, wiring bottlenecks, and power limitations. Therefore, we must return from application-level validation to underlying engineering challenges.

6. Challenges towards more intelligent interfaces

While the diverse applications demonstrate the transformative potential of haptic technologies, it must be objectively acknowledged that current successes are largely confined

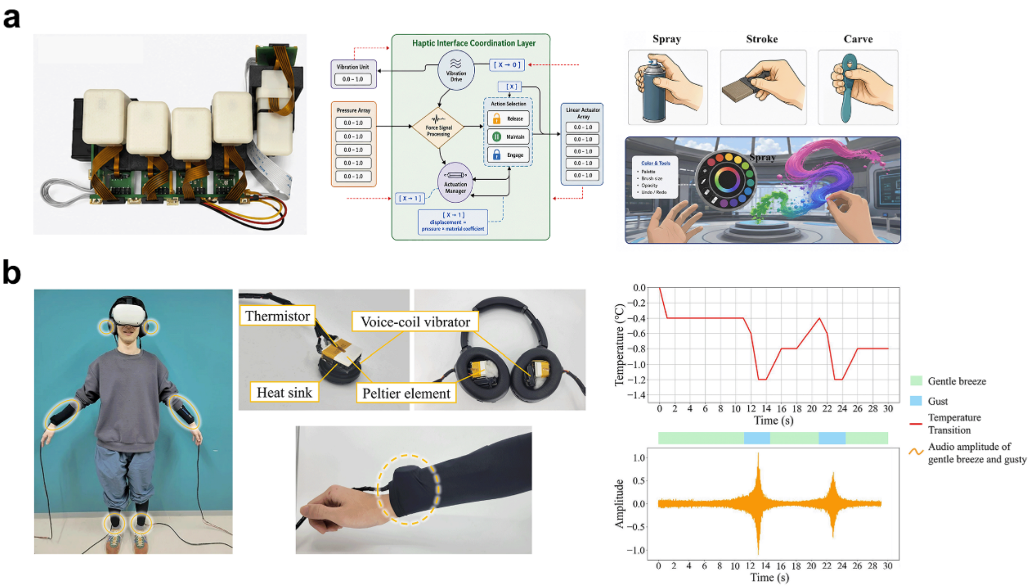

Figure 19. Overview of haptic applications in immersive art and design. (a) Schematic of the five-fingered haptic controller, its interface module diagram, and the concept of the VR drawing tool with spray, brush, and sculpt modes. This specialized controller uses linear actuators to simulate variable damping forces in spraying and carving, letting artists perceive virtual material properties (clay density, paint viscosity) to fill digital art's fine motor control gap and add physical texture to digital creation. (b) Schematic of the integrated hardware-stimulation system, including an HMD, headphone-type haptic devices (for ear vibrotactile/thermal stimulation) and modular devices (for arms/legs, mounted under sleeves). Stimulation diagrams detail synchronized vibrotactile, thermal, and audio-visual feedback. Gentle breezes feature constant mild cooling and low-amplitude vibration, while gusts involve gradual temperature drops, intensified vibration, and dynamic audio. Adapted with permission [174]. Copyright 2025, ACM.

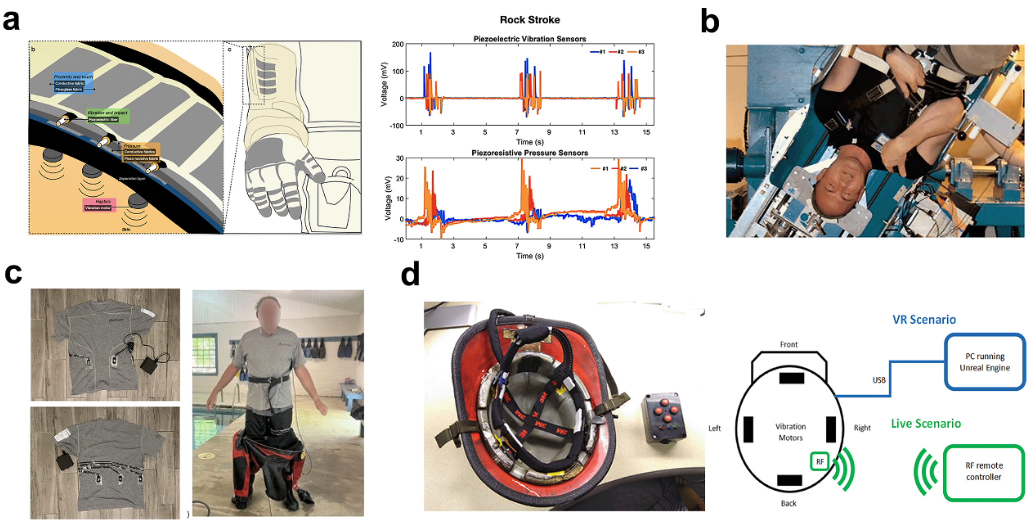

Figure 20. Overview of haptic systems for extreme environments and mission-critical operations. (a) Exploded view of the multi-modal e-textile spacesuit skin and diagram of sensor responses (piezoelectric vibration and piezoresistive pressure) for rock stroke motions. While piezoresistive pressure signals are qualitatively similar across different strokes, the rocky surface induces longer-duration piezoelectric ringing, indicating distinct material interaction signatures. Reproduced with permission [157]. Copyright 2021, IEEE. (b) Photograph of an astronaut familiarizing with the Tactile Orientation Awareness Support Tool (TOAST) in a rotating chair, where a tactor on the right shoulder vibrates to indicate the 'down' direction. Reproduced with permission [176]. Copyright 2007, Springer Nature. **c** Photographs of the Triton Systems vibrotactile garment (front and back) and a schematic illustration of the tactor-integrated garment worn underneath a dry suit. Reproduced with permission [177]. Copyright 2025, Elsevier. (d) Schematic of the haptic helmet prototype and its connectivity diagram. This haptic helmet's tactile feedback system can translate directional cues and mission-critical commands into distinct vibration patterns via its embedded motors, achieving reliable command transmission for firefighters in extreme environments. Reproduced with permission [158]. Copyright 2020, Springer Nature.

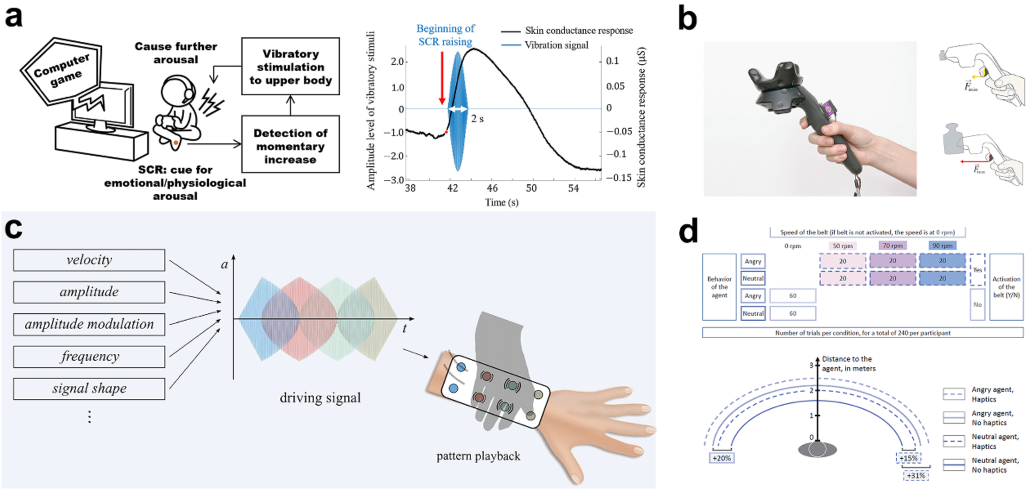

Figure 21. Overview of consumer-grade haptic applications in interactive entertainment. (a) Schematic of the emohance system concept and representative waveform example. The system detects momentary skin conductance response (SCR) increases to trigger upper-body vibratory feedback, with a 2 sec vibration output precisely synchronized to the SCR rising phase, demonstrating a closed-loop mechanism linking physiological arousal to haptic stimulation. Reproduced with permission [180]. Copyright 2025, IEEE. (b) Photographs of the Triggermuscle haptic controller and its continuous trigger resistance adjustment demonstration. The adaptive trigger simulates variable mechanical resistance matching the weight of virtual objects, enhancing the kinesthetic realism of virtual grasping. Reproduced with permission [181]. Copyright 2022, Frontiers. (c) Schematic of the affective touch rendering system. Parameterized inputs generate signals for the wideband actuator armband, synthesizing social affective touch patterns. Reproduced with permission [182]. Copyright 2023, IEEE. (d) (Top) experimental conditions: agent behavior (angry/neutral), haptic belt activation (yes/no), and belt speed (50/70/90 rpm); (bottom) peripersonal space (PPS) changes with haptics and agent emotion. Haptic feedback boosts threat sensitivity, expanding PPS by 31% when paired with an angry agent in social VR. Reproduced with permission [183]. Copyright 2025, IEEE.

to controlled laboratory environments. Bridging the vast engineering chasm between existing prototypes and the vision of full-sensory immersion requires overcoming a fundamental density, power and latency challenge. Currently, the pursuit of high-resolution tactile feedback invariably introduces a prohibitive wiring clutter in passive matrix architectures, where the exponential growth of taxel density necessitates massive interconnects that compromise the mechanical compliance of flexible devices. Although modular designs using self-healing hydrogels offer a Lego-like reconfigurability to mitigate fixed wiring limitations [139], scaling such approaches to high-density arrays without bulky rigid readout circuits remains an unresolved challenge, distancing current wearables from the conformability of biological skin. Furthermore, the drive for imperceptibility, rendering the interface invisible to the user, clashes with the physical demands of high-fidelity feedback. While wireless, battery-free interfaces based on NFC coupling have achieved skin-integrated form factors [14], their limited power transfer efficiency restricts them to mild vibrotactile cues, failing to support the energy-intensive actuators required for realistic kinesthetic force feedback. This creates a power-portability paradox: the industry is currently forced to choose between lightweight, low-fidelity buzzers and heavy, high-fidelity exoskeletons, with no mature solution yet bridging the gap to a true e-Skin that is both powerful and imperceptible.

Beyond hardware, the signal processing loop faces critical bottlenecks in crosstalk and latency. As sensors evolve toward multimodal fusion (pressure, texture, temperature), signal coupling within micro-nano units becomes inevitable. While backend AI algorithms like 1D-CNNs can softly decouple these signals, this computational overhead introduces inference latency [142]. In the full loop, end-to-end latency exceeding the 50 ms perceptual threshold disrupts the sensory illusion and triggers cybersickness. Consequently, future research must pivot from purely algorithmic compensation toward two promising technical avenues. The first is the exploitation of materials with intrinsic decoupling properties, namely advanced functional materials with innate physical orthogonality that suppress multimodal signal crosstalk at the material level without computational reliance. Such materials encode stimulus-specific transduction pathways at the microscale, enabling native signal isolation via orthogonal physical mechanisms [184, 185]. The second lies in the advancement of in-sensor computing architectures, which process raw sensory signals at the physical source to mitigate transmission latency and maintain immersive sensory consistency.

At the system integration level, these inherent multimodal bottlenecks manifest more acutely as two core challenges: multimodal crosstalk and temporal synchronization. Multimodal sensors integrating thermal and pressure functions frequently suffer from thermomechanical crosstalk, where intrinsic thermal effects induce spurious pressure signals and degrade sensing precision. Jo *et al* [186] demonstrated that temperature-induced charge transport variations in both TFTs and piezoresistive sheets cause severe thermomechanical crosstalk, generating spurious pressure signals and drastically degrading detection accuracy. Meanwhile, high-fidelity immersive systems require sub-millisecond temporal alignment across tactile, visual, and auditory streams, as even small asynchronies break perceptual coherence and degrade embodiment in precision-critical applications. Liang and Yang [187] verified that cross-modal asynchrony above 10 ms impairs immersion, with sub-millisecond alignment critical for embodied perception. Their experiments showed reducing onset error from 23.5 ms to 8.7 ms boosted cross-sensory immersion by 47.3%. Addressing these bottlenecks necessitates both advanced material designs for physical interference mitigation and high-speed cross-modal coordination frameworks.

7. Conclusion

This review has mapped the haptic technology landscape for immersive VR/AR, traversing from biomimetic sensing mechanisms and multimodal feedback actuation to intelligent system integration and vertical application validation. The analysis reveals that haptic interaction is currently at a pivotal window, transitioning from discrete component stacking to system-level fusion. While visual and auditory technologies have successfully constructed the window of the metaverse, only by closing the 'Sensing-Computing-Feedback' physical loop can we break the boundary between virtuality and reality, achieving the qualitative leap from being merely online to being truly on-life.

A defining characteristic of the current state is the disparity between input and output capabilities. On the input, that is sensing side, flexible sensor technologies have achieved super-human sensing to a certain extent, surpassing biological skin in spatiotemporal resolution and successfully decoupling pressure, texture, and temperature. However, the output side remains constrained by physical scaling laws. Compared to the extreme thinness of sensors, high-fidelity kinesthetic feedback still relies on bulky mechanical or pneumatic structures, creating an interaction gap characterized by 'fine input but coarse output.' In this context, the computing layer serves as the critical adhesive, utilizing AI algorithms not only to correct the non-linear drift of flexible electronics but to bridge the semantic gap between raw signals and user intent. From wearables to digital-neural symbiosis, a vast chasm still separates current engineering practice from the ideal form. The ultimate goal is the imperceptible e-skin, which represents a self-healing, self-powered, and breathable interface that mechanically matches biological tissue. Yet, current implementations remain at the stage of wearable peripherals, plagued by wiring complexity and the power-latency trade-off. To bridge this gap, future breakthroughs will require the deep coupling of material science (for bio-integration), edge computing (for zero-latency processing), and system engineering (for integrated manufacturing). In conclusion, the maturation of haptic interaction marks the upgrade of the internet from information transmission to experiential transmission. Only when digital touch becomes as ubiquitous and indistinguishable as vision will the true digital twin era arrive.

8. Future perspectives

The pursuit of next-generation immersive VR/AR fuels continuous innovation in haptic research. Future breakthroughs hinge on the coordinated development of material design, in-sensor computation and system fabrication. These core branches jointly resolve crosstalk, latency and poor conformability, while practical application requirements further refine their implementation routes. All relevant research priorities are categorized into four detailed directions as follows.

(1) Bio-integrated and intrinsically decoupled functional materials

Material innovation constitutes the fundamental physical cornerstone for breaking through multimodal interference and optimizing skin conformal fitting performance. Future material-oriented research shall prioritize the exploitation of novel functional substances with inherent physical orthogonal characteristics, which can realize microscale spontaneous separation of pressure, temperature and texture signals via intrinsic material transduction mechanisms, removing the dependence on post-processing algorithmic decoupling and cutting subsequent computational overhead. Meanwhile, developing ultrathin, high-stretchability and excellent biocompatible composite materials matching human skin's mechanical modulus remains a key research focus. Such optimized substrates support long-term imperceptible wearable deployment, achieve seamless lamination with biological epidermis, substantially upgrade the fidelity of bionic tactile collection, and lay solid material prerequisites for the ultimate realization of full-natural-simulated e-skin. Additionally, self-healing and self-powered functional material modification will become a crucial supplementary research direction, helping tackle the persistent power bottleneck and structural damage failure issues restricting wearable long-duration operation.

(2) In-sensor intelligence for zero-latency multimodal processing

In-sensor and edge computing acts as the core computational engine to suppress full-loop delay and reduce system power consumption. Conventional cloud-based centralized computing requires round-trip data transmission and post-hoc artificial intelligence calculation, inevitably introducing obvious time lag, destroying cross-sensory synchronization and inducing VR motion sickness triggered by sensory mismatch. Subsequent explorations ought to further optimize diversified in-sensor computing hardware architectures, enabling raw thermal, pressure and texture data to complete feature extraction and semantic parsing right at the physical sensing end, fundamentally abolishing intermediate data transmission delay. Embedding lightweight, dynamically adjustable neural network algorithms into on-chip edge units facilitates real-time noise filtering, multi-physical signal separation and high-level intent understanding, accomplishing sub-millisecond synchronization among touch, sight and audition, and steadily maintaining immersive sensory consistency for complex VR interactive scenes. Moreover, neuromorphic computing inspired by biological neural networks will continuously boost the environmental adaptive capacity of tactile intelligent hardware.

(3) Integrated manufacturing for scalable, robust haptic systems
Advanced integrated manufacturing is the indispensable technical carrier translating material and algorithmic innovations into industrial-grade available products. Most current haptic prototypes adopt discrete component splicing assembly, plagued by cumbersome wiring layout, poor mechanical durability and inconsistent batch performance. Future system engineering research will focus on large-area monolithic integrated fabrication techniques that integrate sensing, driving and computing units into a unified compact architecture. Rational topological optimization of overall system layout effectively simplifies internal wire layout, improves structural anti-fatigue deformation capacity and optimizes whole-machine energy efficiency. Forming unified design specifications and universal calibration standards further stabilizes device output performance across robotic teleoperation, clinical rehabilitation and immersive entertainment scenarios, greatly accelerating the commercial transformation of laboratory-based haptic prototypes.

(4) Scenario-customized hierarchical haptic optimization
Diversified practical application demands put forward differentiated customization requirements for haptic system parameters. Targeted hierarchical optimization oriented to specific scenes will be an important developmental tendency. For medical rehabilitation scenarios, haptic parameters need to be fine-tuned in accordance with individual patients' neural recovery conditions to realize personalized rehabilitation training feedback; for industrial remote operation, hardware is optimized toward high-precision force perception and anti-interference ability under harsh environments; for consumer-grade VR entertainment, priority is given to lightweight design and cost control while guaranteeing basic tactile immersion. Scenario-oriented customized development shortens the landing cycle of haptic products and speeds up the popularization of immersive tactile technology in metaverse-related industries.

In conclusion, the four research directions complement one another organically. Coordinated advances across these four dimensions will steadily narrow the gap between existing prototypes and ideal bionic e-skin, facilitating the full commercialization of high-fidelity VR/AR haptic systems.

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Conflicts of interest

The authors declare no conflict of interest.

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