

Bistable haptic textiles for immersive somatosensory augmentation and sensory substitution

Received: 30 September 2025

Accepted: 3 July 2026

Published online: 03 August 2026

 Check for updates

Zhuang Zhang ^{1,2,10}, Sentao Chen ^{2,3,10}, Zihang Yang ^{4,10}, Luoqian Emu^{2,10}, Pingdong Wei ², Chen Jia¹, Yue Liu², Wei Yan², Yao Lu², Yi Huang⁵, Chengpeng Chai², Xurong Gao², Yun-Hsuan Chen ², Hongjian Jiang⁶, Yuhan Jiang^{2,7}, Huaping Wu⁴, Li Hu ⁸, Mohamad Sawan ^{2,9}, Zhongxiang Ding⁷, Zhongxue Gan¹ & Hanqing Jiang ^{2,9} 

The skin's extensive surface and dense mechanoreceptors make it a powerful yet underused channel for conveying complex information through touch. While wearable haptic technologies have advanced human–computer interaction, existing systems remain constrained by limited feedback diversity, localized coverage and discomfort from rigid or adhesive-based designs. Overcoming these constraints is essential for advancing somatosensory communication and immersive human–machine interfaces. Here we present a garment-compatible bistable soft-pneumatic textile interface that enables full-body, multimodal tactile feedback by integrating elastic bistable shells and soft-pneumatic textile compartments. This system generates a broad spectrum of programmable haptic cues—including pressing, vibrating, sliding and high-impact striking—with single actuators delivering up to 14 N of force and array-level control supporting distributed spatiotemporal tactile rendering. Quantitative physiological and perceptual evaluations demonstrate reliable neural activation and discrimination across multiple haptic modes. These findings establish a scalable, energy-efficient platform for immersive virtual environments, tactile communication and assistive sensory substitution, highlighting the potential of textile-based haptics for next-generation wearable somatosensory augmentation.

Unlike visual or auditory stimuli, which can be consciously ignored and are more susceptible to deteriorate with age or fatigue, tactile input commands immediate attention and elicits instinctive reactions, making it an indispensable sensory channel for environmental awareness, safety and emotional connection^{1–4}. The skin's mechanoreceptors have evolved distinct specializations: the fingertips, densely packed with Meissner's corpuscles and Merkel's disks, are exquisitely sensitive and underpin most haptic technologies^{5,6}, with applications in entertainment, training,

medical therapy and rehabilitation^{7–12}. By contrast, the torso has fewer mechanoreceptors but spans a much larger area¹³. This unique combination of extensive coverage and functional tactile sensing remains largely unexplored in haptics. However, it holds strong potential as a large-area sensory surface for full-body tactile information delivery beyond the constraints of fingertip-focused interfaces^{14–17}.

Recent advances in bioelectronics have extended conventional haptic devices into wearable formats targeting torso-based touch

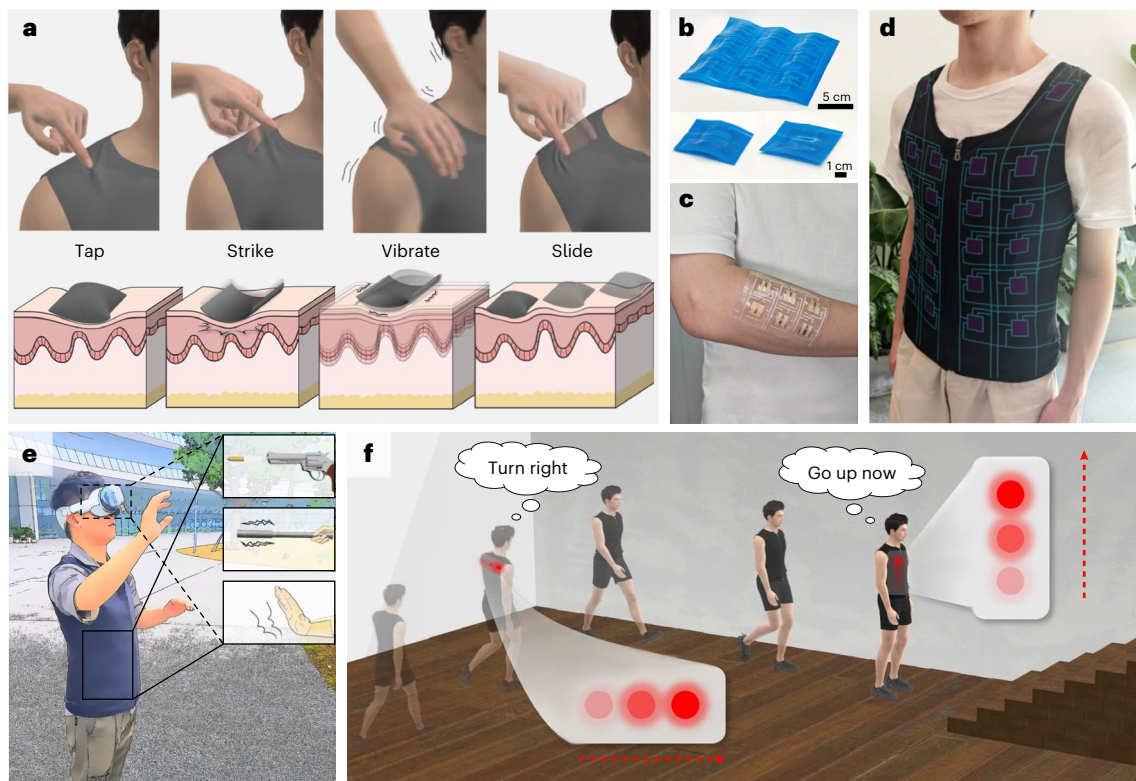


Fig. 1 | Bistable textile interface for multimodal full-body haptic interaction. **a**, Everyday tactile sensations replicated by the textile haptic actuator, enabling multimodal seamless skin-compatible interactions. **b**, Photograph of the haptic actuator in two stable states and a 3×3 actuator array. **c**, Transparent version of the actuator array on an arm, showing the internal structure. **d**, Haptic vest

with array of actuators (purple squares) and air channels (blue lines). **e**, Example of digital sensory replication. Users feel haptic feedback synchronized with virtual interactions. **f**, Example of physical sensory substitution. Users receive navigation directions via full-body haptics.

sensation^{18–24}. However, most wearable haptic systems rely on electromagnetic or electrostatic actuation, limiting them to unimodal feedback (for example, vibration and indentation) with low force tunability^{25–34}. These systems fall short of reproducing the richness of natural touch, for example, its dynamic force gradients, sustained pressure or spatial progression, and require continuous power input even for static feedback. Furthermore, most designs rely on skin adhesives for attachment^{19–27}, a strategy that is incompatible with the body's natural motion and prone to skin irritation. These limitations remain roadblocks to harnessing touch as a robust channel for delivering sensory information and enabling human–machine communication.

To address these challenges, we present a textile-based, bistable soft-pneumatic haptic interface for full-body, multimodal somatosensory interaction, transforming the torso into a programmable sensory surface for spatiotemporal tactile information delivery. This wearable system replaces rigid components and adhesives with elastic bistable shells embedded in thermoplastic urethane textile compartments. It delivers diverse tactile interactions, including gentle taps, forceful strikes, rhythmic drumming and sliding motions with tunable amplitude and frequency, enabling the programmable rendering of daily touch-like cues with distinct spatiotemporal and force characteristics (Fig. 1a and Supplementary Fig. 1). The core innovation lies in a lightweight, multipouch architecture, where layered thermoplastic urethane textiles enclose bistable shells (Fig. 1b). Triggered by pneumatic inputs, these shells harness snap-through transitions between two mechanically stable states to generate diverse tactile outputs without sustained energy input. Monolithic air channels and a scanning-based actuation strategy minimize external hardware, making the system scalable to vests, armbands and full-body wearable suits (Fig. 1c,d).

This bistable haptic system enables precise spatiotemporal control over individual actuator units, creating programmable tactile

sensations such as pressing, vibrating and sliding motions. These multimodal tactile cues facilitate deep immersion in virtual reality (VR)/augmented reality (AR) environments (Fig. 1e) and elicit both objective physiological and subjective perceptual differences. In addition, the interface's spatiotemporal touch patterns provide structured tactile information pathways on the torso, serving as an alternative channel for information delivery in scenarios where visual input is limited (Fig. 1f). Combining multimodal haptic feedback, high force fidelity, energy-efficient operation enabled by bistable state retention and textile-level integration, this platform offers a scalable solution for next-generation human–machine interfaces and context-aware wearable systems.

Design and operation principles of multimodal haptic actuation

The ability to exert multimodal forces with tunable amplitude on human skin is achieved through the integration of two mechanically distinct components: a soft textile air pouch and a hard elastic bistable shell encapsulated in textile, forming a bistable soft-pneumatic actuation. Figure 2a shows a schematic illustration of a single functional unit of this haptic interface, hereafter referred to as the haptic actuator. At the core of this haptic actuator is a curved, bistable copper shell sandwiched between textile layers, while patterned thermoplastic urethane layers form four independent air pouches between the textile-encapsulated bistable shell and the outer textile layers, two pouches above and two below the shell, arranged in perpendicular orientations. Details of the shell geometry, textile encapsulation, pouch formation and channel design are provided in the Methods, Extended Data Figs. 1 and 2, Supplementary Figs. 1 and 2 and Supplementary Notes 1 and 2. Notably, the soft and lightweight textile structure does not compromise the mechanical stability of the bistable shell.

The haptic actuator achieves multimodal force outputs through various inflation strategies applied to four pouches, effectively mimicking single-point tactile interactions, such as impact, vibration and press (Fig. 2b). Inflation of these pouches causes the bistable shell to switch between its two mechanically stable states once the supplied energy surpasses the energy barrier. The switching between the stable states, combined with pneumatic actuation, constitutes the core operating principle of the haptic actuator (Fig. 2c, with more theoretical details in Extended Data Fig. 3, Supplementary Note 3 and Supplementary Fig. 4). Each stable state of the bistable shell is cylindrically shaped: state (1) has a finite κ_x and a vanishing κ_y , whereas state (2) reverses this configuration, featuring a finite κ_y but a vanishing κ_x . The orthogonal nature of the principal axes of these states explains the strategic placement of the air pouches above and below the bistable shell. On inflating the upper pouches, a bending moment opposing the initial curvature of state (1) is applied. When the shell reaches its critical transition state (that is, $\kappa_x = \kappa_y = 0$, state (3)), it instantaneously flips to state (2). The transition is fully reversible: inflating the lower pouches induces the opposite bending moment, following the (2)→(3)→(1) pathway, enabling repeatable actuation. The bistable behaviour of the shell is highly dependent on the design parameters κ_{anneal} and κ_{press} (Fig. 2d), as detailed in the Methods, Extended Data Fig. 3 and Supplementary Note 3. Figure 2e shows a calculated phase diagram of the bending energy as a function of the curvatures κ_x and κ_y , clearly illustrating the energy valleys at states (1) and (2) and the energy peak at state (3). The shell switches between states following the least-energy pathway, highlighted as a solid trajectory in the diagram.

Three distinct force output modes are achieved by strategically varying inflation patterns across the four pouches. Figure 2b shows these three haptic modes, their corresponding actuation strategies and the instantaneous stresses generated on the actuator, the bistable shell and the skin phantom during interaction, with more details on the finite element analysis provided in the Methods, Extended Data Fig. 4, Supplementary Videos 1–3 and Supplementary Figs. 5–7.

In impact mode, inflating the upper pouches while keeping the lower ones deflated stores strain energy in the bistable shell. Once this stored energy surpasses a geometry-dependent threshold, the shell undergoes a snap-through transition to state (2), delivering a rapid strike to the skin through instantaneous energy release. This abrupt force application produces a distinct impact sensation, which is unattainable with conventional pneumatic-driven devices, where force gradually increases with pressure buildup (Supplementary Fig. 8). Notably, once the snap-through threshold is reached, further inflation of the upper pouches is unnecessary, eliminating the need for continuous energy input after activation, thereby enabling energy-efficient operation. In vibration mode, as only a small volume change in the pneumatic pouch is required to trigger snap-through of the bistable shell, swift alternating inflation between the upper and lower pouches drives the bistable shell to oscillate between states (1) and (2), creating a pneumatic-driven vibration mode. This mechanism enables a frequency of up to 10 Hz, constrained by the commercial solenoid

valve used. In press mode, inflating the lower pouches while keeping the upper ones deflated activates the press mode. In this mode, the bistable shell acts as a constrained dome, reinforcing the pressing force on the skin by restricting the upward expansion of the lower pouches.

Figure 2f shows the multimodal force measurements of the haptic actuator on a skin phantom, with additional experimental details in the Methods and Extended Data Fig. 5. In impact mode, the actuator generates high-magnitude forces of up to 14 N within an extremely short duration of ~0.5 ms, consistently under 1 ms. This rapid force delivery results from the instantaneous energy release of the bistable shell, producing a pronounced impact sensation. While input pressure influences actuation time, it has minimal effect on the force magnitude, as the force is primarily determined by the stored elastic energy. Consequently, the generated impact is dictated by the bistable shell's material composition and geometric properties, rather than the actuation source.

In vibration mode, the actuator delivers periodic, stable force outputs at tunable frequencies (Supplementary Video 2). The bistable shell still undergoes rapid snap-through during each cycle, producing transient force peaks even in the vibration mode. As a result, the output waveform shows a pulse-like profile. The force magnitude in this mode is lower than that in impact mode because the air pouches on the opposite side remain partially inflated to enable rapid re-inflation at short intervals, while also introducing a cushioning effect. In press mode, the force gradually increases with applied pressure, but reaching peak force requires notably longer times. Unlike impact mode, where force output is primarily independent of input pressure, press mode exhibits a direct correlation between the applied pressure and the magnitude of the force. By integrating these three force modes, each with distinct magnitudes and frequency characteristics, the haptic actuator generates a broad, quantifiable range of tactile effects, enabling versatile haptic interactions.

Large-area, spatiotemporal haptics

Multiple haptic actuators can be seamlessly integrated into a single textile substrate, forming a full-body wearable haptic interface. This design offers advantages over traditional interfaces made from rigid or rubbery materials by allowing the actuators to be embedded in a garment-like format, thereby improving wearability and supporting repeated washing (Supplementary Fig. 9; Methods). As shown in Supplementary Figs. 10 and 11, which displays 22 actuators on the front and 24 on the back, this configuration supports wearable, large-area, multipoint haptic interactions while eliminating the time-consuming, labour-intensive and often uncomfortable process of adhering multiple discrete actuators directly to the skin. Instead of using a cumbersome one-to-one control scheme, we adopted a scanning-based AND logic control strategy using two independent sets of textile pouches (Methods). Two independently actuated pouches, termed the row pouch and column pouch, are positioned on either side of each bistable shell and serve as inputs for state switching. This scanning-based control uses main air channels to interconnect all row and column pouches, analogous to a main bus in communication systems

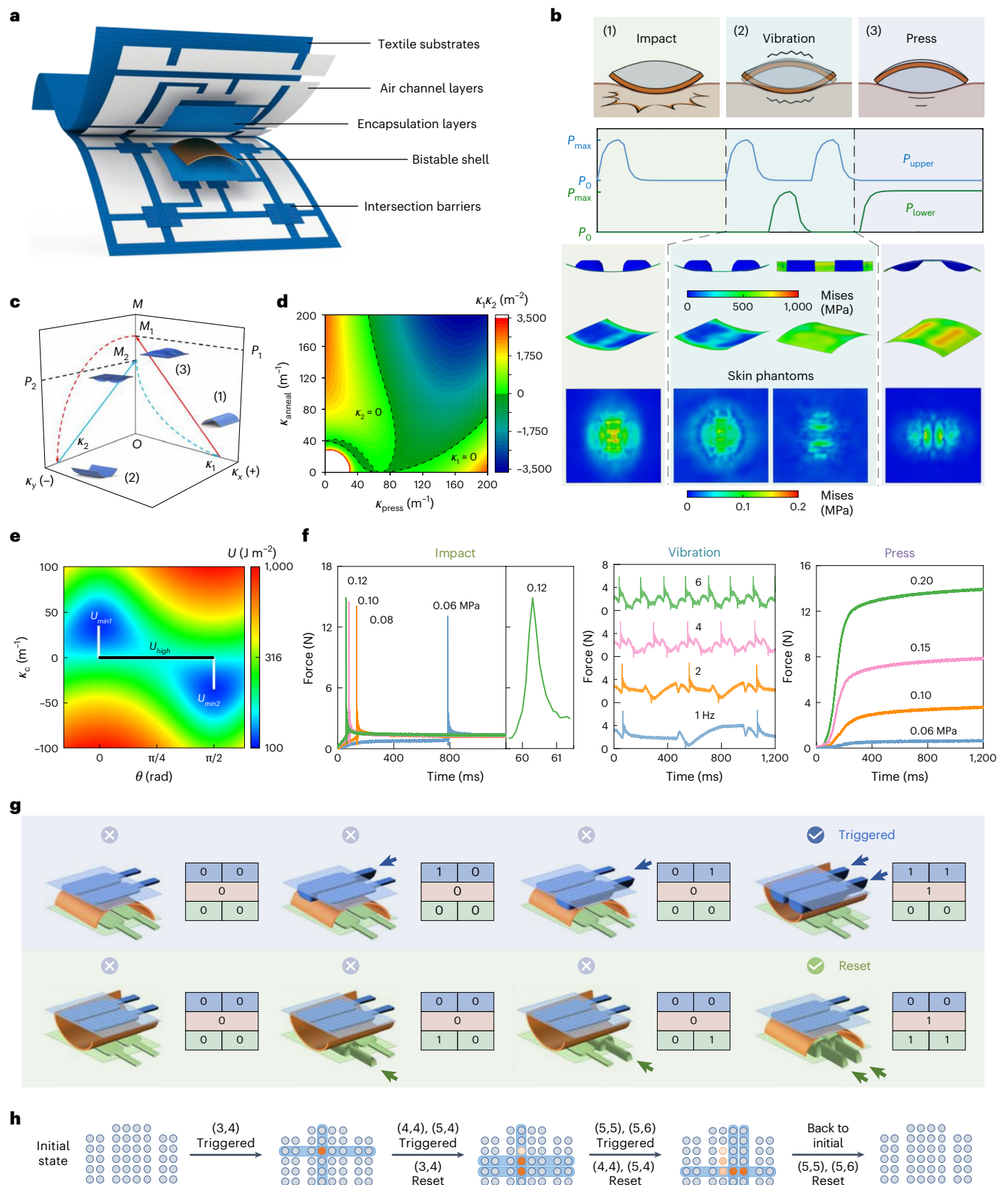
Fig. 2 | Bistable mechanics and scalable multimodal haptic feedback.

a, Exploded view of the haptic actuator showing key components. **b**, Schematics of the three haptic modes (impact, vibration and press), along with their respective actuation strategies and finite element method-simulated stress distributions in the components (from top to bottom: actuator, bistable shell and skin phantom). P_{upper} and P_{lower} denote the input pressure to the upper and lower pouches, respectively. **c**, Schematics of the moment landscape during bistable flapping. κ_1 and κ_2 denote the curvatures of the shell at stable states (1) and (2), respectively. State (3) represents the unstable state with the highest deformation energy. κ_x and κ_y are the perpendicular curvatures representing the bending directions. P_1 , P_2 and M_1 , M_2 are the pressure thresholds and required moments to overcome the bistable shell's energy barrier. **d**, Phase diagram of the bistable

behaviour, where the product $\kappa_1\kappa_2$ is plotted against fabrication parameters, namely, curvatures during annealing κ_{anneal} and pressing κ_{press} . Negative $\kappa_1\kappa_2$ are marked in the shadow area, indicating the existence of bistable behaviour. **e**, Phase diagram of the strain energy storage per unit area (U) in the bistable shell. κ_c and θ represent the curvature and the rotation angle of a curved shell cut from a cylindrical surface (Supplementary Note 3 and Supplementary Fig. 4). **f**, Temporal output force profiles for impact (input pressure 0.06–0.12 MPa), vibration (frequency 1–6 Hz) and press (input pressure 0.06–0.2 MPa) modes. **g**, AND control logic for a single actuator: the bistable shell switches only when both upper or both lower pouches are pressurized simultaneously. **h**, Directional sliding sensations through sequential haptic actuation.

(Supplementary Figs. 12 and 13). Using this approach, individual actuators can be controlled with significantly fewer air sources; for example, a 6×8 array requires 28 rather than 96 controls. This reduction makes integration of an on-body pneumatic system feasible (Methods), greatly improving scalability and overall system efficiency.

Figure 2g shows the actuation mechanism of a single actuator unit driven by an AND logic control strategy. The bistable shell switches state only when both pouches on the same side are simultaneously pressurized above a defined threshold (0.06 MPa), as confirmed by controlled experiments (Supplementary Video 3 and



Supplementary Fig. 14). This logic enables selective activation at the intersection of row m and column n , effectively preventing crosstalk and unintended triggering. Consequently, each actuator embedded within the wearable array, demonstrated here as a vest, can be addressed with spatiotemporal precision and programmed to deliver varying force amplitudes and distinct haptic modes. In addition, multipoint synchronized actuation is achieved by scanning multiple rows and columns concurrently, allowing for customized interaction areas (Fig. 2h and Supplementary Fig. 15). The lower pouches, operating under the same principle, allow bistable shells to be reset during scanning intervals. This enables sequential actuation through coordinated control of the upper and lower pouches. This mechanism generates diverse sliding sensations with varied trajectories, enriching the haptic interaction experience. Note that the system-level latency from command input to full actuation is ~43 ms for a single haptic actuator and ~57 ms for the multipoint haptic vest (Supplementary Fig. 16; Methods), which is sufficient for the interaction scenarios introduced in the following sections.

Physiological responses and information processing from multimodal interactions

Beyond the intuitive skin deformation, the multimodal touch sensations generated by the haptic actuator have the potential to elicit both physiological and cognitive responses (Fig. 3a). To further evaluate these responses and analyse differences among various haptic modes, we conducted quantitative measurements of multiple skin deformation patterns and their corresponding user reactions. Figure 3b shows the temporal profiles of skin phantom indentation across seven actuation modes, including impact (M1), low-/medium-/high-frequency vibrations (M2–M4) and low-/medium-/high-pressure press (M5–M7). Further experimental details are provided in the Methods, Extended Data Fig. 6, Supplementary Figs. 17 and 18 and Supplementary Video 4. Notable differences in skin deformation are observed across various haptic modes, reflecting diverse mechanical interactions and sensory experiences produced by the actuator.

To quantitatively evaluate cognitive differences elicited by haptic interactions, we recruited 12 participants to identify seven actuation modes using a textile-based haptic actuator embedded in a vest-like garment (Fig. 1d). Figure 3c shows the confusion matrix for mode identification. As expected, impact and vibration modes were highly recognizable, with identification rates above 96%, except for medium-frequency vibrations, which were often confused with high-frequency ones. By contrast, press mode showed lower identification rates, especially for high and medium pressures. These results demonstrate that different actuation modes exhibit high distinguishability, with more intense or dynamic interactions being more easily recognized.

To complement subjective cognitive analysis, we recorded objective physiological signals that reflect neural activity. Specifically,

electroencephalographic (EEG) signals were monitored while participants interacted with the haptic vest (Extended Data Fig. 7a). Figure 3d–f shows skin deformation profiles, the mean values of the haptic-evoked potential waveforms and the corresponding scalp topographies for impact, press and vibration modes. The impact mode (Fig. 3d), which elicited a salient, high-intensity tactile sensation, produced substantial variations in amplitude, indicating a strong neural response. By contrast, the press mode (Fig. 3e) showed no distinct waveform features, suggesting that gentle touches produce minimal neural activation. Meanwhile, the vibration mode (Fig. 3f) exhibited periodic variations and fluctuations, with intervals precisely matching the input vibration frequency. Scalp topographies further demonstrate substantial increases in activity in central regions during both impact and vibration modes (more scalp topography representations are shown in Extended Data Fig. 7 and Supplementary Fig. 24). These findings highlight that distinct haptic modes induce specific physiological responses and can be discriminated at the cortical level.

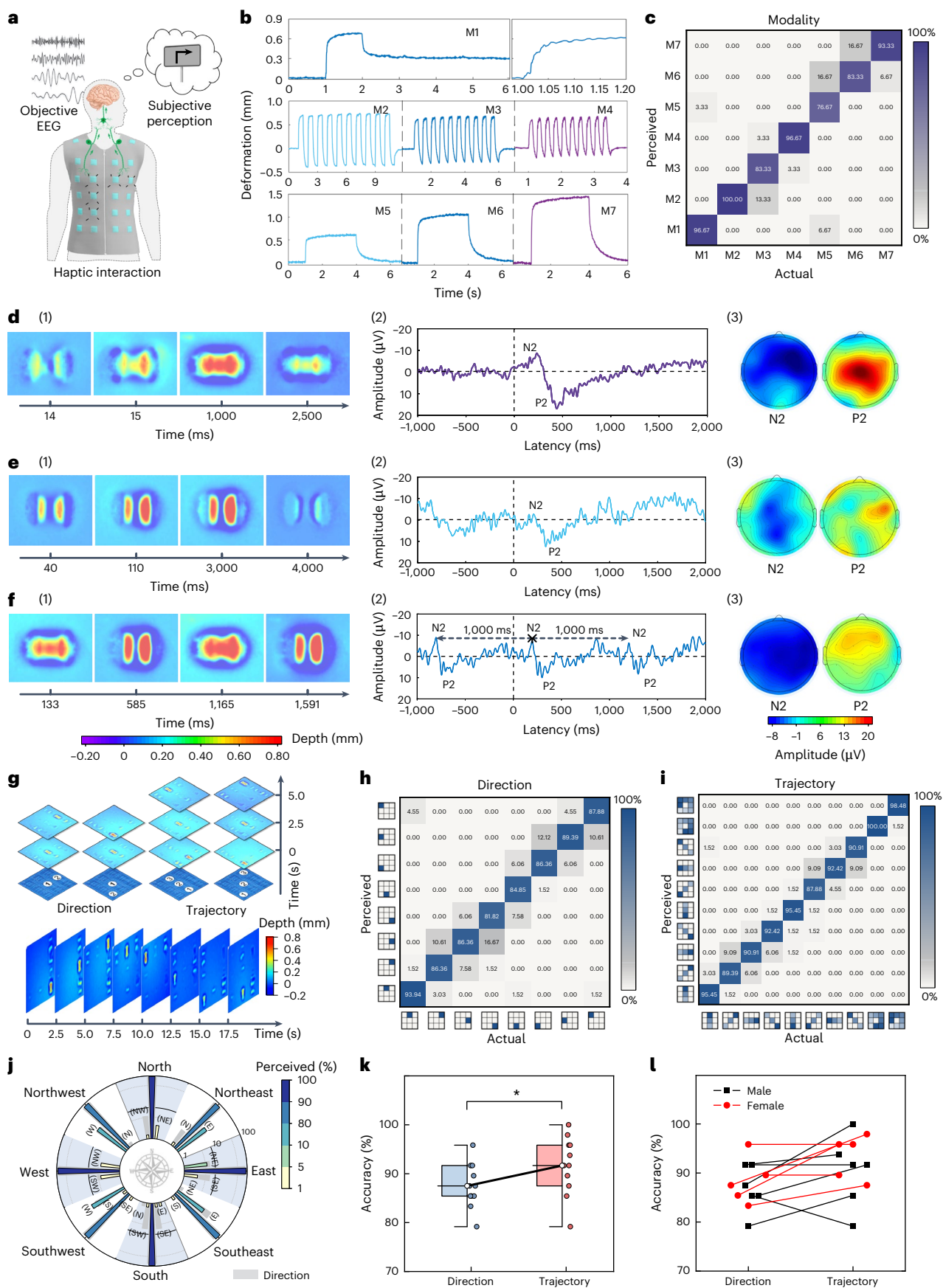
To quantitatively assess the effectiveness of multipoint haptic interactions in conveying spatiotemporal information, we conducted two additional information transmission tests with the 12 recruited participants. These tests included eight relative directions and ten motion trajectories rendered by a 3×3 haptic actuator array embedded in the vest. Figure 3g shows representative continuous skin phantom deformation profiles under various haptic inputs for directions and trajectories (Extended Data Fig. 8 and Supplementary Figs. 25 and 26). The confusion matrix for spatial information shows that identification rates for directions exceeded 81%, demonstrating the system's high accuracy in differentiating interaction positions across a large-area haptic interface (Fig. 3h and Extended Data Fig. 8c). Furthermore, identification rates substantially improved when temporal information was incorporated, allowing participants to perceive sliding trajectories (Fig. 3i and Supplementary Figs. 27 and 28). A statistical analysis further confirms that spatiotemporal trajectory interactions achieved higher recognition rates across all directions compared with static spatial direction interactions (Fig. 3j, Supplementary Fig. 29 and Supplementary Table 1). The improvement in identification rates for trajectory-based interactions showed no significant difference between male and female participants (Fig. 3l). Overall, the high recognizability of spatiotemporal multimodal interactions highlights the potential of this haptic interface for efficient and precise information transmission.

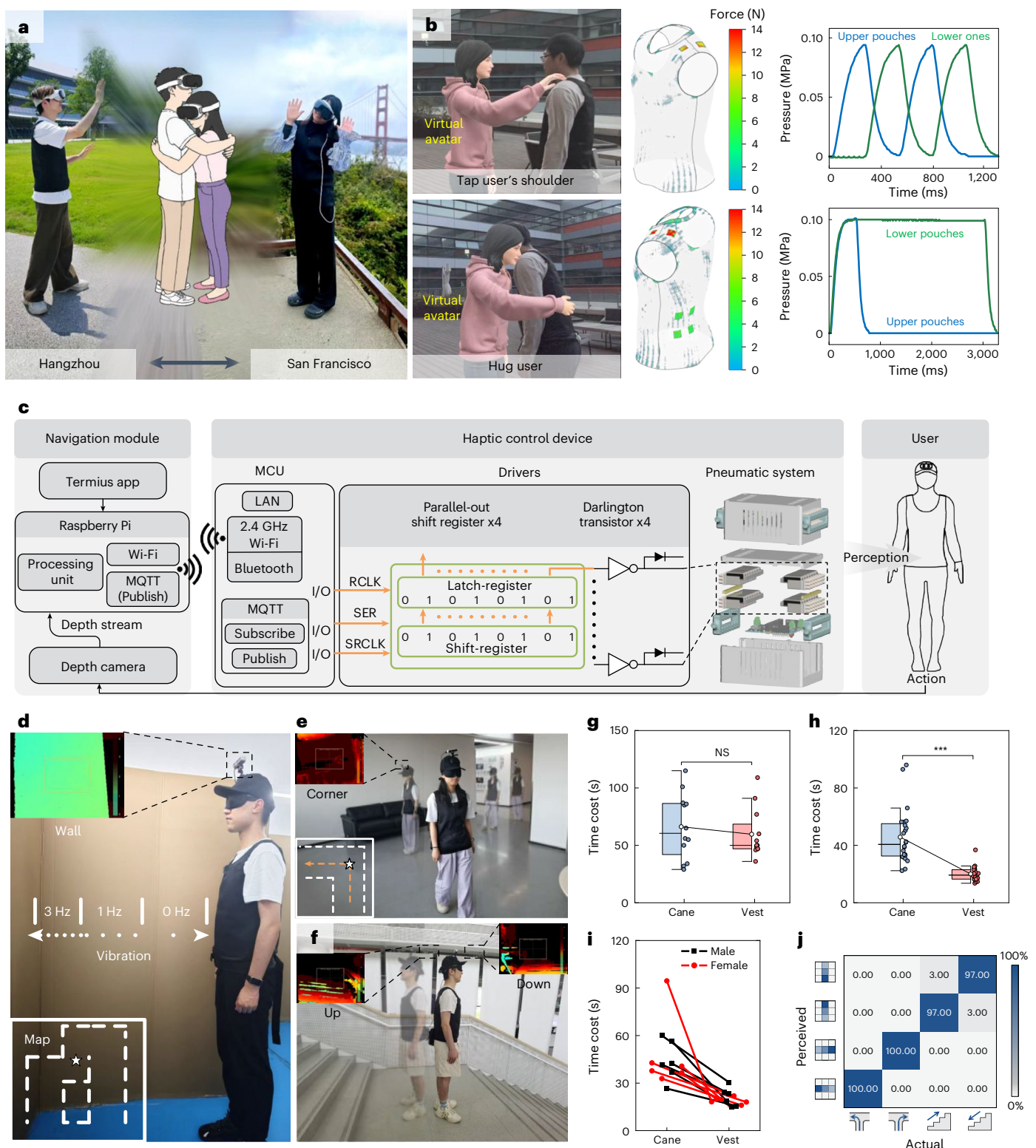
Enhanced virtual perception and real-world sensory substitution

Effective information transmission via multimodal full-body haptic feedback offers two key applications. (1) Sensory replication: reproducing natural touch sensations in VR/AR and remote communication to enhance the immersion and realism. (2) Sensory substitution: leveraging haptic feedback to convey various information through

Fig. 3 | Physiological and cognitive responses induced by multimodal haptic feedback. **a**, Schematics illustrating passive (physiological) and active (cognitive) responses to touch sensations. **b**, DIC measurement of phantom skin's deformation across seven haptic modes (M1: impact and an enlarged view of the response near the snap-through transition, highlighting the rapid local deformation around the snapping point; M2–M4: 1-, 2- and 4-Hz vibration; M5–M7: 0.05-, 0.1- and 0.15-MPa press). **c**, Confusion matrix showing identification rates of 12 participants for seven haptic modes. **d–f**, DIC-measured phantom skin's out-of-plane deformation (1) and EEG responses (2) and (3) for impact (**d**), 0.1-MPa press (**e**) and 1-Hz vibration (**f**). The EEG results in (2) and (3) show the trial-averaged haptic-evoked potential waveforms derived from the Cz channel and the scalp topographies on the basis of full-channel recordings for each mode, obtained from repeated measurements in one participant. N2 and P2 represent the negative and positive ERP components triggered 200 ms after stimulation. **g**, Representative examples of the temporal profile of the continuous skin phantom's deformation measured by DIC under two directional cues (northeast and southeast) and three trajectory cues (bottom-up, bottom-left to top-right and counterclockwise).

These panels illustrate different example cases rather than a single continuous activation sequence. **h, i**, Confusion matrices showing identification rates of 12 participants for eight directions (**h**) and ten trajectories (**i**). **j**, Polar diagram comparing identification performance for direction and trajectory interactions. Coloured bars indicate trajectory interactions, whereas grey bars indicate direction interactions. In each fan-shaped sector, the bars show the distribution of participants' recognized answers for the corresponding directional cue. Misread results are displayed near the correct sector, and the letters in parentheses indicate the misread directions. **k**, Statistical analysis showing significant improvement of identification rates for trajectory interactions compared with direction interactions (paired two-sided t -test, $P = 0.035$; $n = 11$; bars, 1.5 IQR; shaded box, range between 25th and 75th percentiles; horizontal lines, medians; open circles, means; points, individual participants). Asterisk denotes significant effects at $*P < 0.05$ (paired two-sided t -test). **l**, Individual performance variability between direction and trajectory interactions across participants ($n = 11$ independent participants; points, individual participants; lines connect paired measurements from the same participant).





an additional tactile channel without interfering with existing sensory modalities in the head and hands. This may also provide an alternative access pathway for individuals with visual or auditory impairments.

By integrating the haptic perceptions from our textile interface with synchronized visual information from commercialized VR/AR devices (for example, Vision Pro, Apple), we establish representative scenarios for a more immersive and 'touchable' virtual experience. Designed to be worn like everyday clothing (shown in Fig. 4a,b), this interface enables embodied interactions across physical and virtual

environments beyond conventional audiovisual communication. The interface's multimodal capabilities facilitate a wide range of interactions. For example, as shown in Fig. 4b (more details in the Methods, Extended Data Fig. 9a,b and Supplementary Video 5), when a virtual avatar or a remote user taps the wearer's shoulder, the haptic interface produces a 2-Hz vibration at that location, mimicking two consecutive taps within 1 s. Similarly, during a virtual embrace, the haptic interface delivers synchronized tactile feedback: an impact on the front chest to simulate a firm head bump and a press around the lower back to

Fig. 4 | System implementation for physical–digital somatosensory replication and substitution. **a**, Schematics of remote touch interactions enabled by the present haptic interface. **b**, Illustrations of virtual avatar interactions: a 2-Hz vibration is delivered to the shoulder when tapped by a virtual avatar; an impact on the chest and pressure around the waist simulate a hug. Heat maps display force distribution, accompanied by corresponding pneumatic input signals for the upper (blue) and lower (green) pouches. **c**, System integration and circuit diagram illustrating the closed-loop haptic navigation. LAN, local area network. **d**, Photograph of a user navigating a maze, guided by vibration cues mapped to obstacle distance. **e,f**, Photographs of the 3D navigation via different haptic trajectory cues to direct users to turn (**e**) or move up/down (**f**). **g**, Statistical analysis showing that the haptic interface performs similarly to the white cane in narrow-space navigation tasks (paired two-sided *t*-test, $P = 0.223$; $n = 11$; bars,

1.5 IQR; shaded box, range between 25th and 75th percentiles; horizontal line, median; open circles, means; points, individual participants). NS, not significant. **h**, Statistical analysis showing significant improvement in turn-making efficiency during everyday scenarios with the haptic interface compared with the white cane (paired two-sided *t*-test, $P < 0.001$; $n = 11$; bars, 1.5 IQR; shaded box, range between 25th and 75th percentiles; horizontal line, median; open circles, means; points, individual participants). Three asterisks denote significant effects at $***P < 0.001$ (paired two-sided *t*-test). **i**, Individual differences by two navigation methods (haptics and white cane) across participants ($n = 11$ independent participants; points, individual participants; lines connect paired measurements from the same participant). **j**, Confusion matrix showing identification rates of 12 participants across four open-space navigation scenarios.

replicate arms wrapping around the user's waist. Quantitative comparison with representative daily human interactions further shows that the rendered haptic cues exhibit good correspondence in force magnitude and temporal profile (Supplementary Fig. 30 and Supplementary Note 4). In addition, VR games and training programmes can benefit from this wearable interface by enriching tactile immersion in interactive scenarios. For example, in police-versus-criminal simulations, applicable to both gaming and law-enforcement training, users can experience a range of tactile sensations, from the impact of a hit to the vibration of a taser or the pressure of an opponent's palm (Extended Data Fig. 9c–e, Supplementary Fig. 31 and Supplementary Video 5). These haptic effects can vary in location and intensity, enabling spatially and temporally coordinated tactile feedback in response to virtual interactions.

To demonstrate the practical application of sensory substitution, we developed a haptic navigation system that integrates the wearable haptic interface, a pneumatic source, drivers and a microcontroller unit (MCU), communicating with an onboard navigation module (Fig. 4c). This navigation module captures real-time visual information using a portable camera or a smartphone and transmits these data to the MCU via a Wi-Fi connection, enabling corresponding haptic feedback (see the Methods and Supplementary Figs. 32 and 33 for details). The system conveys detected environmental data to the user through haptic stimuli, aiding in real-time decisionmaking. As the user moves and surroundings change, newly detected depth information is continuously updated, forming a closed-loop guidance framework.

To preliminarily evaluate sensory substitution from visual to touch perception, we conducted two demonstrations with 12 participants. The first demonstration used a navigation system that detected obstacle distances and converted them into distinct vibration frequencies, to guide participants through a maze (Fig. 4d, Extended Data Fig. 10a,b, Supplementary Fig. 34 and Supplementary Video 6). The second demonstration used image identification to facilitate navigation in larger space, using multipoint spatiotemporal haptic interactions, such as different trajectories, to guide turning decisions and stair ascent/descent (that is, three-dimensional (3D) navigation, shown in Fig. 4e,f, Extended Data Fig. 10c,d, Supplementary Video 6 and the Methods). Figure 4g,h shows a comparison of the time participants took to navigate a maze and make decisions at intersections using a traditional white cane versus our haptic interface. Results show that our device substantially improved efficiency in making turns during everyday scenarios, reducing the mean completion time from 41.33 s with the white cane to 20.25 s with the haptic interface for both male and female participants (Fig. 4i), and performed comparably to the white cane in navigating narrow spaces (more details in the Methods, Extended Data Figs. 10e–g and Supplementary Tables 2–4). In addition, user accuracy in directional choices (100%) and stair navigation (97%) indicate the practical feasibility of the haptic interface for navigation (Fig. 4j), with only one instance of stair misjudgment.

Conclusion

This study establishes a textile-based, multimodal haptic interface as a wearable platform for full-body somatosensory communication. By harnessing mechanically programmable bistability within a soft, garment-compatible architecture, the system delivers spatially and temporally controlled multimodal feedback, including impacts, vibration and sustained pressure, while overcoming the limitations of unimodal, rigid or adhesive-based haptic systems. Beyond enhancing immersion in VR and AR, the platform introduces a scalable strategy for encoding and decoding tactile information across the torso, effectively transforming it into a programmable sensory surface. Its compatibility with human physiology and perception enables use not only in digital environments but also in assistive contexts such as navigation and tactile information guidance. The observed haptic-evoked physiological responses further support the interface as a non-invasive channel for wearable human–machine communication. More broadly, these results suggest a scalable route towards perception-oriented wearable systems for tactile information delivery and interactive sensation.

Nevertheless, the current design focuses on multimodal haptic feedback primarily through normal force-based interactions, which are well suited for garment-scale systems requiring large-area coverage and high-output force actuation architectures. Tangential cues induced by shear and torsional skin deformation^{18,22} are not directly realized at the single-actuator level in the present implementation. An important future direction is to integrate both normal and tangential force modalities within textile-compatible haptic platforms to enable more comprehensive haptic interaction. In addition, future improvements could also focus on localized breathable textile integration and lightweight structural optimization in areas where airtightness is not required, further enhancing long-term wearability.

Methods

Fabrication of the bistable shell

The bistable shells were fabricated via sequential annealing and roller pressing processes, as shown in Extended Data Fig. 1a. Beryllium copper (QBe2) sheets with a thickness of 0.20 mm were first precision-cut into rectangular shapes using a metal laser cutting machine (CFZ0604, LTGC). After that, thermal annealing was performed to induce the primary curvature (κ_{anneal}). The sheets, clamped within a grooved thermal forming mould, were subjected to simultaneous mechanical pressing and controlled heating in a muffle furnace at 316 °C for 4 h under a nitrogen atmosphere, followed by natural cooling to room temperature (Extended Data Fig. 1a, step 1). This process relieved residual stresses and established the initial stable state (state ①).

To introduce a secondary, orthogonal curvature (κ_{press}), the annealed shells were reoriented and mechanically deformed via roller pressing in a second grooved mould (Extended Data Fig. 1a, steps 2–3). This process redistributed internal stresses, yielding a bistable geometry capable of snap-through transitions between two mechanically stable states (Extended Data Fig. 1a, step 4). For integration into

textile-based actuators, each bistable shell was laminated between two thermoplastic polyurethane (TPU)-coated textile sheets. The assembly was sealed along all four edges using thermal bonding at 230 °C for 5 s with a packaging heat sealer (Model-16499, Deli Group) (Extended Data Fig. 1a, step 5). The resulting structure preserved bistability while enabling lamination with other textile layers, ensuring mechanical compliance and compatibility with wearable form factors.

Fabrication of the haptic actuator

The haptic actuator adopts a sandwich structure, with a centrally embedded bistable shell encapsulated between two TPU-coated textile layers. A low-melting-point TPU film serves as an interfacial adhesive, enabling component integration at a reduced processing temperature (140 °C) to avoid thermal deformation of the pneumatic textile substrate. Functional layers are sequentially assembled through precision thermal processing to ensure both mechanical stability and pneumatic functionality.

The fabrication process began with laser-patterning of a low-melting-point TPU film ($T_m = 120$ °C, thickness of 0.2 mm), which was thermally laminated onto a TPU-coated textile substrate via flat-plate pressing (140 °C, 0.2 MPa, 30 s). This process formed embedded air channels by selectively exposing regions of the underlying TPU-coated textile (Extended Data Fig. 1b, step 1). To preserve channel geometry during subsequent bonding steps, a polytetrafluoroethylene (PTFE) dispersion was spray-coated onto the channel surfaces using a masking technique, forming a robust anti-adhesion layer (Extended Data Fig. 1b, step 2). Four TPU-coated textile barriers were then placed at the orthogonal intersections of the channels to separate the upper and lower pneumatic layers. Their functional role is further detailed in Supplementary Note 2. Next, the pre-encapsulated bistable shell was aligned at the geometric centre, thereby defining dual pneumatic chambers between the bistable shell and the base textile layer (Extended Data Fig. 1b, step 3).

The assembly was completed by laminating an orthogonally oriented counterpart as the top layer under identical thermal conditions, thereby forming a fully sealed pneumatic network (Extended Data Fig. 1b, steps 4–5). Finally, four 3D-printed TPU plugs were inserted into the inflation ports and thermally bonded to serve as interfaces for polyurethane (PU) tube (Extended Data Fig. 1b, step 6). This hierarchical, multilayer assembly ensures precise alignment of the bistable shell and robust sealing of the pneumatic structure, enabling reliable snap-through actuation under controlled pneumatic input.

Design details and operating parameters of the haptic actuator

The haptic actuator adopts a textile-integrated bistable soft-pneumatic architecture. The bistable shell is a curved copper shell, 25 mm × 25 mm in surface dimension, 0.20 mm thick and weighing 1.01 g. It is sandwiched between two 0.15-mm-thick textile pieces, 30 mm × 30 mm in dimension and each weighing 0.20 g. This size was selected to balance torso-level perceptual discriminability, stable bistable actuation and wearable textile integration. Reducing the actuator dimensions could increase spatial resolution, but would also reduce effective contact area and output force, and may increase sensitivity to fabrication tolerances and pneumatic resistance. The bistable shell features two mechanically stable states with perpendicular curvatures, κ_1 and κ_2 . These stable states are formed through sequential annealing and pressing processes, defined by κ_{anneal} and κ_{press} , respectively, as described in the shell fabrication section and shown in Extended Data Fig. 1a.

Two transparent thermoplastic urethane layers with precut patterns are used as adhesive and pneumatic structural layers. These layers form four independent air pouches between the textile-encapsulated bistable shell and the outer textile layers. Two pouches are positioned above the shell and two below the shell, with the upper and lower pouch pairs arranged in perpendicular orientations. Strategically placed cutouts and intersection barriers are incorporated into the TPU layers

to maintain crossed air channels and to prevent undesired bonding during thermal lamination. Material and design optimizations used to improve repeatability, sealing and durability are provided in Supplementary Note 1 and shown in Supplementary Fig. 3, while the detailed role of the intersection barriers is provided in Supplementary Note 2 and shown in Extended Data Fig. 2.

The bistable shell switches between two cylindrical stable states. In state (1), the shell has a finite κ_x and a vanishing κ_y ; in state (2), this configuration is reversed. The selected fabrication parameters in this work are $\kappa_{\text{anneal}} = \kappa_{\text{press}} = 100 \text{ m}^{-1}$, which ensure robust bistability. The bistable shells fabricated with these parameters maintain stable switching between states (1) and (2) for over 10,000 cycles, exhibiting robust mechanical behaviour and demonstrating excellent fatigue resistance. The theoretical description of the bistable energy landscape, including the critical transition state and the least-energy switching pathway, is provided in Supplementary Note 3, Extended Data Fig. 3 and Supplementary Fig. 4.

For impact-mode characterization, input pressure affects the time required to reach the snap-through threshold but has minimal effect on the final impact force. In the tested pressure range, the actuation time decreases from 784 ms at 0.06 MPa to 60 ms at 0.12 MPa, whereas the peak force remains within a narrow range, for example, 13.07 N at 0.06 MPa and 14.87 N at 0.10 MPa. This behaviour confirms that the impact force is primarily dictated by the stored elastic energy of the bistable shell rather than by pneumatic pressure directly. This relative insensitivity to actuation pressure indicates robustness to variations in actuation conditions, while the snap-through response of the bistable shell remains stable and repeatable owing to its intrinsic mechanical instability. The snap-through transition itself occurs consistently within ~0.5 ms, indicating that the ultrafast response is an intrinsic property of the shell's mechanical instability. Additional force measurements for impact, vibration and press modes are shown in Extended Data Fig. 5.

Prototyping of the haptic garment

The haptic garment comprises three integrated components: a functional haptic inner layer for tactile feedback, a weskit serving as the outer constraint and a waist bag housing the control system. The weskit substrate, constructed from stretchable neoprene material, provides robust elasticity to maintain consistent contact between the haptic interface and the human body. The functional layer consists of an array of haptic actuators interconnected by a pneumatic network, detachably affixed to the inside of the weskit via Velcro (Supplementary Fig. 11). Following the actuator fabrication process described above, the functional layer was manufactured by laser-patterning TPU-coated textile sheets to define pneumatic channels, followed by thermal lamination of multiple layers to encapsulate the bistable shells. A total of 46 actuators (22 front, 24 back) were spatially distributed at intervals corresponding to 1.5 times the two-point discrimination threshold (2PDT) of the human trunk, ensuring accurate perceptual resolution (Supplementary Figs. 10–13). Along the perimeter of the functional layer, 28 input ports were integrated to interface with tubing connected to the control system. These ports enable independent pressurization and depressurization of individual rows or columns within the pneumatic network, forming the foundation for programmable, multimodal full-body haptic feedback.

Finite element modelling of the haptic actuator during the actuation process

The commercial finite element package ABAQUS was used to simulate the actuation process of the haptic actuator and the corresponding processes of its components. The initial state of the model represents the configuration of the shell after it comes into contact with the skin. To simulate the residual stress introduced during fabrication, a moment load was applied to the curved edge of the shell. Two actuated airbags

were attached to each side of the shell using tie constraints, and pneumatic inflation was simulated by applying a pressure load to the inner surfaces of the airbags. To replicate the physical constraint that causes the shell to conform to the skin, a rigid surface was positioned above the entire structure. To ensure convergence during simulation, the displacement of the central point of the bistable shell was restricted in the z-direction. This constraint stabilized the computational process and improved the accuracy and reliability of the results. Meshing was performed using quadrilateral elements with a global element size of 1 mm, with further local refinement in regions exhibiting high stress concentrations. The simulation adopted the t-mm unit system. The material properties were defined as follows: beryllium copper (QBe2) had a mass density of $8.3 \times 10^{-9} \text{ t mm}^{-3}$, a Young's modulus of $1.28 \times 10^5 \text{ MPa}$, a Poisson's ratio of 0.35 and a critical stress of 1,035 MPa. TPU had a mass density of $5.0 \times 10^{-10} \text{ t mm}^{-3}$, a Young's modulus of 100 MPa and a Poisson's ratio of 0.38.

Finite element modelling of the skin phantom under various haptic modes

A solid mesh was used for the skin phantom model, with local refinement applied in regions in contact with the bistable shell to improve simulation accuracy. Fully fixed boundary conditions were imposed on the bottom surface of the skin, while the remaining boundaries were left unconstrained. The skin material was modelled as linear elastic under the t-mm unit system, with a mass density of $1.0 \times 10^{-9} \text{ t mm}^{-3}$, a Young's modulus of 5.1 MPa and a Poisson's ratio of 0.5. All other simulation parameters were consistent with those used in the modelling of the haptic actuator mentioned above.

Characterization of the haptic actuator

Comprehensive mechanical characterizations were conducted to evaluate the functionality and performance of the haptic actuator, including output force measurements under varied conditions, cyclic durability test and interaction assessments with skin phantoms. Before these mechanical measurements, the effect of textile encapsulation on the mechanical behaviour of the bistable shell was examined (Supplementary Fig. 2). A six-axis force sensor (Mini 45, ATI) was mounted on a height-adjustable stable platform, with the bistable shell placed atop the sensor. A universal testing machine (JHY-5000, Xingsuo Intelligent Equipment) was used to activate the snap-through of the shell. This setup allowed continuous monitoring of the force output throughout the shell's deformation. Tests were carried out for both two-point and single-point activation modes, with and without TPU encapsulation. The results indicated that two-point actuation produced a slightly higher output force than single-point actuation. The reduction of the output force generated from TPU encapsulation is negligible; however, the encapsulation was found to enhance stability during the subsequent vibration process.

Output force measurement. A series of controlled experiments, each isolating a single variable, were performed to quantify output force under diverse actuation conditions. The setup consisted of a rigid base frame supporting the actuator, a six-axis force sensor mounted on a height-adjustable platform and a skin phantom designed to mimic human tissue mechanics. As shown in Extended Data Fig. 5a, the skin phantom was positioned above the force sensor, directly beneath the actuator. The platform height was finely tuned until the phantom made gentle contact with the actuator, with the force reading maintained at zero to ensure baseline consistency.

To assess environmental influences, we first varied the stiffness (Ecoflex 00-30 versus Dragon Skin 00-30), thickness (0.5–4 mm) and separation distance (0–1.5 mm) of the skin phantom (Extended Data Fig. 5b–d). The actuator consistently delivered strong output forces when paired with Dragon Skin 00-30 at 0.5-mm thickness. Maximum force was achieved under direct contact; reductions were negligible for

separation distances less than 0.5 mm. On the basis of these observations, subsequent measurements maintained gentle contact.

For impact mode characterization, the input pressure was varied from 0.06 MPa to 0.12 MPa to generate the pressure–force response curve. In addition, the time required to reach the snap-through point and the corresponding threshold pressure for state transition were recorded (Fig. 2f, impact). For the vibration mode, output force variation curves were obtained at actuation frequencies ranging from 1 Hz to 6 Hz (Fig. 2f, vibration). For the press mode, output forces were measured across a pressure range of 0.06 MPa to 0.20 MPa (Fig. 2f, press).

Cyclic testing. Long-term operational durability was assessed through 10,000 continuous actuation cycles under constant input pressure (0.1 MPa), using the setup shown in Extended Data Fig. 5a. In each cycle, the bistable shell transitioned between its two stable states, and the corresponding force profiles were captured by the force sensor (Extended Data Fig. 2f), confirming mechanical reliability and repeatability.

Response time testing. System-level latency was measured using a custom setup comprising a microcontroller (STM32F1C8T6, STMicroelectronics) controlling solenoid valves (S070C-5BC-32, SMC), a force-sensitive resistor (FSR402, Interlink Electronics) mounted on a rigid aluminium substrate and an organic light-emitting diode (OLED) display for time recording (Supplementary Fig. 16a). The actuator was securely attached to the aluminium plate with the force-sensitive resistor sensing area positioned at the centre to ensure optimal force detection. Response time was calculated from valve activation trigger to force detection by the sensor. Measurements were performed for both single actuators and the multipoint scanning operation within the haptic vest. The single actuator achieved sub-45-ms latency (mean of 43.65 ms; Supplementary Fig. 16c), while the vest-integrated actuator array exhibited a slightly slower response (mean of 57.05 ms), attributable to the more complex pneumatic channel network required for scanned array control.

Washability assessment. The wash durability of the haptic actuator was evaluated following the IEC 63203-204-1:2023 standard for electronic textile wash testing. Single actuators underwent ten consecutive washing cycles in a commercial washing machine using a gentle mode (30 °C water temperature, 45-min duration per cycle) with standard detergent (0.2% concentration) and 2 kg of companion fabrics to simulate practical washing conditions. After each cycle, the actuators were dried at room temperature under natural ventilation. Force–time curves were measured at 2-Hz vibration frequency before and after washing cycles (Supplementary Fig. 9). The actuator maintained functional integrity after repeated washing, with only a 5% reduction in output force amplitude, confirming good wash durability for practical wearable use.

DIC of skin deformation

3D digital image correlation (DIC) was used to quantify the out-of-plane deformation of skin phantoms induced by haptic actuators. Two sets of experiments were conducted: (1) single-actuator tests to measure localized deformation under different haptic modes (that is, impact, press and vibration) and (2) a 3×3 actuator array to capture spatiotemporal deformation patterns (that is, sliding). As shown in Extended Data Fig. 6a,b, the actuators were mounted in contact with a fully transparent skin phantom (40:1 PDMS, 5 mm thickness). Before testing, the top surface of the phantom was uniformly spray-coated with black speckles and then overlaid with a white pigment to generate high-contrast speckle patterns for image tracking (Extended Data Fig. 6c). A binocular high-speed camera system (S1310 equipped with a Canon 24–70-mm lens, Revealer) was positioned beneath the skin phantom to capture the displacement of the surface speckles (1,000 Hz for single-point actuation and 200 Hz for the 3×3 array). The recorded displacement

data were processed using a specialized software package (RDIC-3D) to reconstruct the 3D deformation fields. These results were visualized as contour maps to illustrate the effects of the haptic actuators on the skin throughout the actuation cycle across various haptic modes (Extended Data Figs. 6e and 8b and Supplementary Figs. 17, 18, 25 and 26).

Construction of the actuation system

The actuation system was designed to control the motion behaviour of the haptic actuator by regulating airflow via solenoid valves (S070C-5BC-32, SMC). As shown in Supplementary Fig. 32b, this system comprises an MCU (ESP32-WROOM-32UE, Espressif), a buck converter module, four 8-bit shift registers, four 8-channel Darlington transistor arrays, 28 miniature solenoid valves and a programmable air pump (AD5NKEEDB24PPD, Tidesmart). The MCU integrates 2.4 GHz Wi-Fi and dual-mode Bluetooth functionality. The system is powered by a 24-V battery, and a buck converter (XL1509-3.3, UMW) steps down the voltage to 3.3 V to supply the MCU and shift registers (74HC595PW, Nexperia). The 24-V line is directly connected to the common terminal of the Darlington arrays (ULN2803A, UMW) to drive the solenoid valves. For signal control, the SRCLK (shift register clock) and RCLK (latch register clock) pins of the four 74HC595PW chips are connected in parallel to the clock source of the main controller. The serial output (Q7) pin of each preceding chip is connected to the serial input (SER) pin of the next chip, forming a cascaded chain structure.

On receiving a control signal such as 'x2y4h1500p255v5d0', the microcontroller sequentially transmits data via the SER pin. On each rising edge of SRCLK, a single bit is shifted into the register. A total of 32 SRCLK pulses are required to load 32 bits of data. A subsequent rising edge on RCLK causes all chips to latch the data from the shift register into their storage registers, enabling parallel output via pins Q0–Q7. These outputs drive the Darlington transistor arrays, each channel of which can reach up to 500 mA of continuous current, ensuring sufficient power for actuating multiple miniature solenoid valves simultaneously.

Scanning-based pneumatic control

The scanning-based pneumatic control system adopts a hierarchical architecture that enables spatiotemporal multiplexing of haptic feedback while substantially reducing hardware complexity. As shown in Supplementary Fig. 12, the system consists of two orthogonally arranged pneumatic channel layers: a frontal layer (a) comprising longitudinal channels aligned along the length of the vest and a rear layer (b) comprising transverse channels oriented perpendicularly to the frontal layer. A dual-layer pouch array is laminated onto the textile substrate via selective thermal bonding, on the two sides of the bistable shells. A key design element involves the insertion of textile barriers at channel intersections (Extended Data Fig. 1b, step 3), effectively preventing interference between the two pneumatic layers.

The system operates on the basis of a pressure threshold-dependent AND logic mechanism. Simultaneous pressurization of a selected row and column within the same layer results in inflation of all activated pouches along the intersecting axes. At the row–column junction, the coordinated expansion of two pouches induces a tensile strain exceeding 2%, which is sufficient to trigger the snap-through transition of the embedded bistable shell (Supplementary Fig. 12c). By contrast, single-pouch inflation at non-intersecting locations produces a subthreshold strain (<0.5%), which is insufficient to overcome the shell's snapping barrier, leaving the shell in its current state (Supplementary Fig. 14 and Supplementary Video 3). Resetting the bistable shell is similarly achieved via coordinated pressurization of the corresponding rear-layer pouches (Supplementary Fig. 12d), synchronized with depressurization of the frontal layer. This process reliably reverts the shell to state (1). Compared with direct-addressing pneumatic systems, the scanning-based pneumatic control system

reduces the number of required input ports (namely, the required solenoid valves) by approximately 70% (for example, only 28 ports are needed for a 6×8 array).

Human-participant tests of haptic-mode recognition and physiological responses

To evaluate cognitive differences elicited by haptic interactions, we recruited 12 participants to identify seven actuation modes using a textile-based haptic actuator embedded in a vest-like garment. The seven actuation modes were defined as impact (M1), low-/medium-/high-frequency vibrations (M2–M4) and low-/medium-/high-pressure press (M5–M7). The temporal profiles of skin phantom indentation across these modes were measured by DIC, with experimental details shown in Extended Data Fig. 6, Supplementary Figs. 17 and 18 and Supplementary Video 4. In the confusion matrix for mode identification, the columns represent the present modes and the rows correspond to the participant-identified modes. Individual results for all participants are shown in Supplementary Figs. 19 and 20.

To complement subjective cognitive analysis, EEG signals were monitored while participants interacted with the haptic vest. Three haptic modes, namely, impact, vibration and press, were applied to the same position on the user's waist, with 30 trials per mode. All trials were conducted in a silent, temperature-controlled environment, with participants remaining still and comfortable to minimize sensory interference. Haptic-evoked potential waveforms were derived from the Cz channel, and scalp topographies were obtained from full-channel recordings. N2 and P2 waves were defined as the most negative and positive deflections occurring between 150 and 500 ms after stimulus onset. Details of EEG data collection and preprocessing are shown in Extended Data Fig. 7 and Supplementary Figs. 21–24.

Spatiotemporal information transmission tests

To assess the effectiveness of multipoint haptic interactions in conveying spatiotemporal information, we conducted two information transmission tests with the same 12 recruited participants. These tests included eight relative directions, namely, north, south, west, east and their combinations, and ten motion trajectories, including three-point straight sliding in eight directions, clockwise motion and counter-clockwise motion. A 3×3 haptic actuator array with a spacing of 4 cm was embedded in the vest. This spacing was selected to fall within the reported range of 2PDTs on the torso, allowing neighbouring actuators to remain perceptually distinguishable while maintaining sufficient actuator size for stable bistable actuation and robust force output. The haptic language definitions, including directions and trajectories, are shown in Extended Data Fig. 8a.

Continuous skin phantom deformation profiles were measured under various haptic inputs for directions and trajectories. Measured results of all trials are shown in Extended Data Fig. 8b and Supplementary Figs. 25 and 26. The confusion matrices for direction and trajectory recognition are shown in Fig. 3h,i, Extended Data Fig. 8c and Supplementary Figs. 27 and 28. A statistical analysis was performed to compare recognition performance between spatial direction interactions and spatiotemporal trajectory interactions, with results shown in Fig. 3j,k and Supplementary Fig. 29. In the radar chart, the bars within each fan-shaped region represent the statistical distribution of the participants' recognized answers for the corresponding directions. Misread results are displayed near the correct sector, and the letters in parentheses indicate the misread directions. The improvement in identification rates for trajectory-based interactions showed no significant difference between male and female participants, as shown in Fig. 3l and Supplementary Table 1. In addition, recognition rates for clockwise and counterclockwise trajectories approached 100% for both genders, probably owing to the longer interaction durations and extended motion pathways associated with these trajectories.

Perceptual evaluation of multimodal haptic feedback

To evaluate the various perceptions generated by the present haptic actuator, a single-point recognition experiment was conducted to record participants' ability to distinguish different haptic modes. A total of 12 healthy participants (six males and six females), aged between 20 and 35 years, were recruited for the study. Participants were first briefed on the procedure and completed a simple training session. During training, each participant experienced seven distinct tactile modes applied to the forearm (M1–M7). Each stimulus lasted approximately 15 s, followed by a 15-s rest interval. During testing, each participant completed 21 randomized perception trials. Each of the seven haptic modes was delivered three times in a randomized order, without advance notification of the mode being presented. Each stimulus was delivered for approximately 15 s, with a 15-s interval between trials. Participants were instructed to identify the perceived haptic mode solely on the basis of the haptic sensation, without any audiovisual interference. The sequence of mode presentations was also individually randomized for each participant to eliminate order effects.

All experiments involving human participants, including the physiological experiments in the following, were approved by the Ethics Committee of Westlake University (approval no. 20231221JHQ001). The informed consent of all the experiments was obtained by every participant.

Perceptual evaluation of spatiotemporal information

To evaluate the spatiotemporal information conveyed by the haptic interface, a multipoint perception experiment was conducted involving 12 healthy participants (six males and six females), aged between 20 and 35 years. The experiment consisted of two parts: direction and trajectory perception.

Direction perception. In the direction perception task, each participant was asked to identify which of the eight peripheral actuators in a 3×3 array had been activated. Before the formal experiment, all participants received an explanation of the procedure and completed a simple training session. During training, participants experienced individual actuation of the eight peripheral actuators. Each stimulus lasted 5 s, followed by a 20-s interval. To account for regional perceptual differences between the abdomen and the back, two separate training sessions were performed. After training, direction recognition tests were conducted on both the abdomen and back, with 24 trials for each region (each of the eight peripheral actuators tested three times). As in the single-point experiment, the trial sequences were randomized individually for each participant.

Trajectory perception. The trajectory perception task followed the same training and testing protocols as the direction perception task, with the exception that multiple actuators in the 3×3 array were activated sequentially to generate dynamic trajectory patterns. A total of ten trajectories were tested: four horizontal/vertical, four diagonal and two circular (clockwise and counterclockwise) patterns. For the circular trajectories, all eight peripheral actuators were activated sequentially. For the remaining eight straight trajectories, three actuators, including the central point, were used. Owing to the increased number of actuation points, the duration of each stimulus and the intertrial interval were extended to 15 s. Each participant completed 30 randomized trials for both the abdomen and the back.

Physiological experiment

EEG measurement. The EEG analysis in this study was intended to compare haptic-evoked response patterns across actuation modes, rather than to identify specific cortical sources. A healthy 30-year-old male participant with no history of chronic pain or neurological disorders was recruited for the study. EEG recording was conducted while the participant remained seated in a comfortable chair within a quiet,

temperature-controlled and acoustically isolated room. A 32-channel standard EEG cap (BrainCap and BrainAmp, Brain Products GmbH) was used, with a passband of 0.01–100 Hz and a sampling rate of 1,000 Hz. Conductive gel was applied to each electrode, and impedance was maintained below 10 k Ω across all channels.

To synchronize actuator events with EEG signals, trigger outputs were recorded via electrodes placed behind the ears, using the nose electrode as the reference channel. Before the experiment, the participant was instructed to wash their hair thoroughly and rest for 5 min. To familiarize with the stimuli, all three haptic modes were applied once to the target area. During recording, noise-isolating earplugs were worn to eliminate auditory cues from actuator operation. To prevent adaptation or anticipatory responses, each haptic mode was tested in separate sessions with a minimum 10-min break between them. For impact and press modes, stimulation was delivered with a randomized intertrial interval of 5–9 s (Extended Data Fig. 7b and Supplementary Fig. 24a) to minimize temporal expectancy effects.

Data processing. Pain-related brain responses typically exhibit lower amplitudes than background EEG activity and are often obscured by non-cortical artefacts. Therefore, the analysis of single-trial event-related potential (ERP) requires advanced signal processing techniques to enhance the signal-to-noise ratio. In this study, a combination of band-pass filtering and independent component analysis was used to filter the data in both the frequency and spatial domains, respectively, to remove irrelevant noise and artefacts.

EEG data were analysed using EEGLAB, an open-source MATLAB toolbox. First, frequency-domain filtering was performed using a band-pass filter between 0.1 and 30 Hz. EEG trials were then extracted using a 3,000-ms analysis window, comprising a 1,000-ms prestimulus interval and a 2,000-ms post-stimulus interval. Baseline correction was applied using the prestimulus period (–1,000 ms to 0 ms). Independent component analysis was then used to remove artefacts such as eye movements and muscle noise. Independent components exhibiting strong correlations with electrooculogram channels or fronto-central scalp distributions were excluded from further analysis.

On the basis of the aforementioned processing steps, the raw EEG data from the Cz channel (Supplementary Figs. 21–23) were analysed using the EEGLAB toolbox to generate the ERP waveforms shown in the central panels of Extended Data Fig. 7c,e and Supplementary Fig. 24b. Scalp topographies at representative timepoints were also derived from multichannel data and presented in the surrounding panels.

Construction of the AR/VR scenarios

A mixed reality (MR) environment was developed in Unity 2022 (Unity Technologies) and deployed on an MR device (Apple Vision Pro, Apple). The scene featured a virtual protagonist (that is, the user) equipped with a first-person camera, alongside four non-playable characters (NPCs). The protagonist was programmed to follow the user's real-time physical movements as they navigated the environment wearing the MR device. Three male NPCs were animated to perform distinct haptic-triggering actions, including electrocution, hand pressing and baseball throwing. A female NPC was programmed to simulate shoulder-tapping and hugging. All character animations were initially created in Blender, where rigging was performed using Blender's Rigify plugin, followed by manual frame refinement. To enhance realism, additional motion assets from the Mixamo library were blended into the animations. The completed animations were imported into the Unity environment, which was connected to a local server and interfaced with the haptic system.

The MR environment was linked to the haptic interface via a Message Queuing Telemetry Transport (MQTT) communication framework, using a publish/subscribe model. For example, a topic named 'collision' was published to a server. When a virtual object made contact with the user's avatar in the MR scene, spatial collision data were

transmitted under this topic. The haptic system subscribed to this topic and responded in real time.

When the system is operated on a computer (Mac mini, Apple), with the user wearing both the MR device and the haptic interface, the system triggered context-specific tactile feedback, such as vibration, impact and pressure, corresponding to in-game interactions. For instance, if the protagonist was struck by a virtual electric rod, a hand or a fast-moving baseball thrown by a male NPC, the system generated appropriate haptic feedback at the corresponding body location. Similarly, interactions from the female NPC—such as shoulder taps or hugs—resulted in synchronized pressure or vibration feedback delivered through the wearable haptic interface.

Construction of the closed-loop navigation system

The closed-loop navigation system consisted of two major components: a navigation device and a wearable haptic interface. These two components communicated via an Internet of Things (IoT) communication protocol based on the publish/subscribe model. The navigation device primarily comprised a depth-sensing camera (RealSense D435i, Intel) and a single-board computer (SBC) (Raspberry Pi 5, Raspberry Pi Foundation). The camera continuously captured real-time depth data from the surrounding environment, while the SBC processed the incoming data and generated corresponding haptic navigation commands. Depending on the proximity and spatial configuration of obstacles relative to the user, the system issued two types of tactile feedback: (1) collision warning signals in the form of variable-frequency vibration and (2) walk guidance in the form of directional sliding.

Visual sensory substitution test

Two experimental scenarios were used to evaluate the performance of haptic navigation system in comparison with a conventional white cane. A total of 12 healthy participants took part in the study. The test environments included: (1) a simple maze structure measuring 2.7 m in length, 2.7 m in width and 2.4 m in height and (2) an L-shaped indoor corridor with a total walking path of approximately 10 m (Extended Data Fig. 10 and Supplementary Fig. 34). Note that each participant completed both the white-cane condition and the haptic-device condition. The order of the two conditions was not fixed and varied across participants. A 30-min interval was provided between the two conditions.

During the maze navigation tests, each participant was blindfolded to eliminate visual input. As the participants moved through the environment, the depth-sensing camera continuously captured real-time spatial information. The depth stream was transmitted to the SBC, which calculated the distance to nearby obstacles and generated the corresponding vibration feedback. For instance, when an obstacle was detected within 1 m ahead of the user, the system generated a 1-Hz vibration signal to the haptic interface. As the obstacle approached within 0.5 m, the vibration frequency increased to 3 Hz to signal heightened urgency. The participants were able to identify obstacle-free directions and navigate accordingly by turning their heads and perceiving on-body vibrations.

For directional guidance in a more general daily environment, the navigation device analysed the spatial distribution of surrounding obstacles to determine whether a left or right turn was required. For instance, when a right turn was detected, a directional haptic command was transmitted, triggering a sequential left-to-right actuation across the body. This produced a directional haptic sensation to guide user movement. The haptic interface continuously subscribed to spatial cues provided by the camera in real time and executed appropriate haptic feedback according to the decoded environmental data.

Data analysis and statistics

Four statistical tasks were conducted to evaluate human perception and navigation performance using the haptic actuator and the vest. Task 1 was a multimodal haptic perception evaluation assessing participants'

ability to distinguish among seven distinct haptic modes (M1–M7). Task 2 involved a directional haptic perception assessment requiring participants to identify directional cues on the basis of haptic signals under two feedback modes: direction mode and trajectory mode. Tasks 3 and 4 compared navigation performance between the haptic vest and a white cane in an intersection-turning task and a maze navigation task, where completion times were recorded for both devices.

Four independent groups of participants were recruited ($n = 12$ per group; six males and six females), with each group assigned to one task. Throughout all experiments, participants wore blindfolds and noise-isolating earplugs to eliminate environmental visual and auditory cues, ensuring reliance solely on their haptic feedback.

For the multimodal haptic perception task (task 1), 12 participants completed a single-point recognition experiment comprising a training session and 21 randomized trials (three repetitions $\times$ seven modes). Participant-level data cleaning was performed using a box plot analysis (whiskers, 1.5 interquartile range, IQR), and two participants were identified as statistical outliers and excluded. No individual trials were selectively removed. This resulted in a final sample of ten participants, corresponding to 30 valid trials per mode. The results showed robust discriminative capability across all seven haptic modes (Fig. 3c). Notably, the impact (M1) and vibration modes (M2–M4) achieved near-perfect identification accuracy ($>96\%$), with M2 (1 Hz vibration) reaching 100%. Among the press modes (M5–M7), the identification accuracy increased with applied pressure, from 76.67% (M5, 0.05 MPa) to 83.33% (M6, 0.1 MPa) and 93.33% (M7, 0.15 MPa), which indicated a positive correlation.

For the directional perception and navigation tasks (tasks 2–4), three additional independent groups of participants were recruited ($n = 12$ per group; six males and six females), with each group assigned to one task. Sample sizes for paired t -tests were estimated using PASS software ($\alpha = 0.05$, power of 0.8). For task 2, preliminary data ($n = 5$) indicated a mean difference (δ) of 5.42% (paired standard deviation $\sigma = 4.80\%$), yielding a required sample size of nine. For tasks 3 and 4, pilot testing ($n = 5$) revealed a mean time difference of 23.91 s ($\sigma = 10.30$ s) for the turning task and 11.40 s ($\sigma = 12.16$ s) for the maze navigation, necessitating 4 and 11 participants, respectively. To ensure statistical consistency across all tasks, the largest estimated sample size (namely, 11) was conservatively rounded up to 12 participants per group. Participant-level data cleaning was again performed using box plot analysis (whiskers, 1.5 IQR). For task 2 shown in Fig. 3h,i, 1 participant was excluded as a statistical outlier, resulting in an effective sample size of 11 participants and 66 trials per direction (each participant completed 6 trials per direction, comprising 3 trials on the abdominal and 3 trials on the back skin). For tasks 3 and 4 (Fig. 4g–j), 1 participant was excluded as a statistical outlier, yielding a final sample of 11 participants and 33 trials per task.

All data were demonstrated to be normally distributed, determined using the Shapiro–Wilk test ($P > 0.05$ for all comparisons) before analysis for statistical significance (Supplementary Table 1), and paired t -tests were therefore applied for their hypothesis testing (Supplementary Table 2). The haptic perception test revealed a significant difference in directional accuracy between the directional mode (mean (M) = 87.50%, s.d. = 4.56%) and trajectory mode (M = 91.67%, s.d. = 6.04%), indicating that the trajectory mode enhanced haptic perception ($P < 0.05$). In the turning task, participants wearing the haptic vest completed the task significantly faster (M = 20.25 s, s.d. = 4.56 s) compared with using the white cane (M = 41.33 s, s.d. = 9.65 s), demonstrating the vest's efficiency in navigation ($P < 0.001$). No significant difference was observed in the maze task between the haptic vest (M = 59.67 s, s.d. = 21.57 s) and white cane (M = 66.25 s, s.d. = 28.37 s), suggesting comparable performance ($P > 0.05$). Extended Data Fig. 10e–g shows the effects of gender on maze and turning-task performance. Independent-samples t -tests confirmed no significant performance differences between genders in either task (Supplementary Table 3).

Reporting summary

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

Data availability

All data generated or analysed during this study are included in this Article and its Supplementary Information.

Code availability

The code that supports the analysis of the electroencephalographic (EEG) data is available via GitHub at <https://github.com/EMLQ/BHT>.

References

- Ackerman, J. M., Nocera, C. C. & Bargh, J. A. Incidental haptic sensations influence social judgments and decisions. *Science* **328**, 1712–1715 (2010).
- Lederman, S. J. & Klatzky, R. L. Haptic perception: a tutorial. *Atten. Percept. Psychophys.* **71**, 1439–1459 (2009).
- Verrillo, R. T. *Sensory Research: Multimodal Perspectives* (Psychology Press, 2014).
- Hertenstein, M. J., Holmes, R., McCullough, M. & Keltner, D. The communication of emotion via touch. *Emotion* **9**, 566–573 (2009).
- Zimmerman, A., Bai, L. & Ginty, D. D. The gentle touch receptors of mammalian skin. *Science* **346**, 950–954 (2014).
- Handler, A. & Ginty, D. D. The mechanosensory neurons of touch and their mechanisms of activation. *Nat. Rev. Neurosci.* **22**, 521–537 (2021).
- Qi, J. et al. Bridging the digital–physical divide using haptic and wearable technologies. *Nat. Electron.* **7**, 1098–1110 (2024).
- Gerald, A. & Russo, S. Soft sensing and haptics for medical procedures. *Nat. Rev. Mater.* **9**, 86–88 (2024).
- Zhang, Z. et al. Active mechanical haptics with high-fidelity perceptions for immersive virtual reality. *Nat. Mach. Intell.* **5**, 643–655 (2023).
- Panzirsch, M. et al. Exploring planet geology through force-feedback telemanipulation from orbit. *Sci. Robot.* **7**, eabl6307 (2022).
- Fagogenis, G. et al. Autonomous robotic intracardiac catheter navigation using haptic vision. *Sci. Robot.* **4**, eaaw1977 (2019).
- Jumet, B. et al. Fluidically programmed wearable haptic textiles. *Device* **1**, 100059 (2023).
- Corniani, G. & Saal, H. P. Tactile innervation densities across the whole body. *J. Neurophysiol.* **124**, 1229–1240 (2020).
- Prattichizzo, D., Chinello, F., Pacchierotti, C. & Malvezzi, M. Towards wearability in fingertip haptics: a 3-DoF wearable device for cutaneous force feedback. *IEEE Trans. Haptic* **6**, 506–516 (2013).
- Culbertson, H., Schorr, S. B. & Okamura, A. M. Haptics: the present and future of artificial touch sensation. *Annu. Rev. Control Robot. Auton. Syst.* **1**, 385–409 (2018).
- Kang, B. et al. A flexible skin-mounted haptic interface for multimodal cutaneous feedback. *Nat. Electron.* **8**, 818–830 (2025).
- Kang, S. et al. An 18-g haptic feedback ring with a three-axis force-sensing skin. *Nat. Electron.* **8**, 1234–1246 (2025).
- Ha, K.-H. et al. Full freedom-of-motion actuators as advanced haptic interfaces. *Science* **387**, 1383–1390 (2025).
- Yu, X. et al. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature* **575**, 473–479 (2019).
- Jung, Y. H. et al. A wireless haptic interface for programmable patterns of touch across large areas of the skin. *Nat. Electron.* **5**, 374–385 (2022).
- Park, M. et al. Skin-integrated systems for power efficient, programmable thermal sensations across large body areas. *Proc. Natl Acad. Sci. USA* **120**, e2217828120 (2023).
- Flavin, M. T. et al. Bioelastic state recovery for haptic sensory substitution. *Nature* **635**, 345–352 (2024).
- Leroy, E. & Shea, H. Hydraulically amplified electrostatic taxels (HAXELs) for full body haptics. *Adv. Mater. Technol.* **8**, 2300242 (2023).
- Wang, Y. et al. Multiscale haptic interfaces for metaverse. *Device* **2**, 100326 (2024).
- Yao, K. M. et al. Encoding of tactile information in hand via skin-integrated wireless haptic interface. *Nat. Mach. Intell.* **4**, 893–903 (2022).
- Youn, J.-H. et al. Skin-attached haptic patch for versatile and augmented tactile interaction. *Sci. Adv.* **11**, eadt4839 (2025).
- Guo, Y. et al. Haptic artificial muscle skin for extended reality. *Sci. Adv.* **10**, eadr1765 (2024).
- Sun, Z., Zhu, M., Shan, X. & Lee, C. Augmented tactile-perception and haptic-feedback rings as human-machine interfaces aiming for immersive interactions. *Nat. Commun.* **13**, 5224 (2022).
- Lee, D.-Y. et al. A wearable textile-embedded dielectric elastomer actuator haptic display. *Soft Robot.* **9**, 1186–1197 (2022).
- Ji, X. et al. Untethered feel-through haptics using 18- μ m thick dielectric elastomer actuators. *Adv. Funct. Mater.* **31**, 2006639 (2021).
- Li, Z. et al. Air permeable vibrotactile actuators for wearable wireless haptics. *Adv. Funct. Mater.* **33**, 2211146 (2023).
- Bilal, O. R. et al. A flexible spiraling-metasurface as a versatile haptic interface. *Adv. Mater. Technol.* **5**, 2000181 (2020).
- Williams, S. R., Suchoski, J. M., Chua, Z. & Okamura, A. M. A 4-degree-of-freedom parallel origami haptic device for normal, shear, and torsion feedback. *IEEE Robot. Autom. Lett.* **7**, 3310–3317 (2022).
- Campanelli, A. et al. Innovative multi vibrotactile-skin stretch (MuViSS) haptic device for sensory motor feedback from a robotic prosthetic hand. *Mechatronics* **99**, 103161 (2024).

Acknowledgements

We thank X. Wang, D. Liu, X. Chen and J. Luowu for helping with human experiments.

Author contributions

Z.Z., S.C. and Hanqing Jiang developed the concept. Z.Z., S.C., Z.Y. and Hanqing Jiang designed and prototyped the devices. Z.Z., L.E., Y. Lu and Y.H. developed the electronics, the control system and the software. Z.Z., S.C., Z.Y., L.E., P.W., C.J., Y. Liu, W.Y., Hongjian Jiang, Y.J., H.W., L.H., Z.D., Z.G. and Hanqing Jiang carried out experiments and analysis. Z.Z., S.C., Z.Y., L.E., C.C., X.G., Y.H.C. and M.S. collected the user data. Z.Z., S.C., Z.Y., L.E. and Hanqing Jiang wrote the paper.

Funding

This study was supported by the National Key R&D Program of China (grant no. 2024YFB4707500) and the National Natural Science Foundation of China (grant nos. 12350003, 52575011, U25A20294 and 12372168).

Competing interests

The authors declare no competing interests.

Additional information

Extended data is available for this paper at <https://doi.org/10.1038/s44460-026-00120-5>.

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s44460-026-00120-5>.

Correspondence and requests for materials should be addressed to Hanqing Jiang.

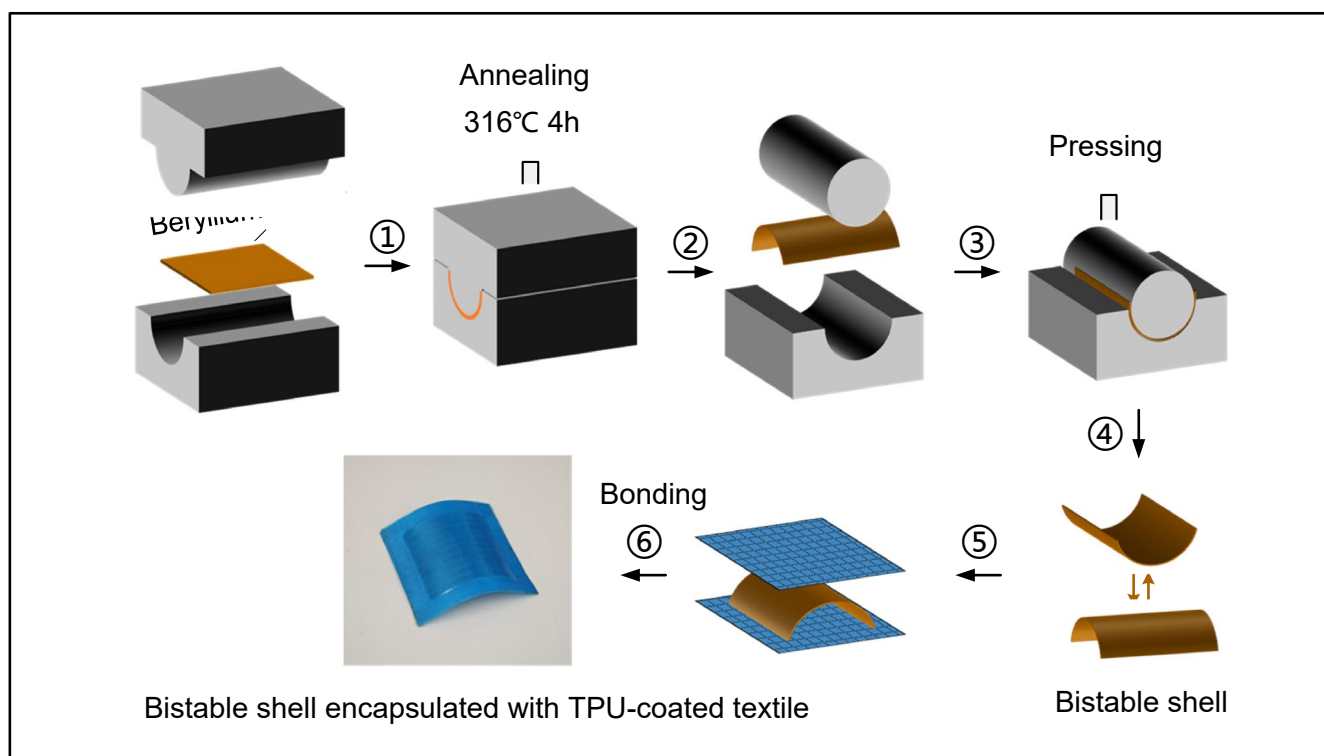
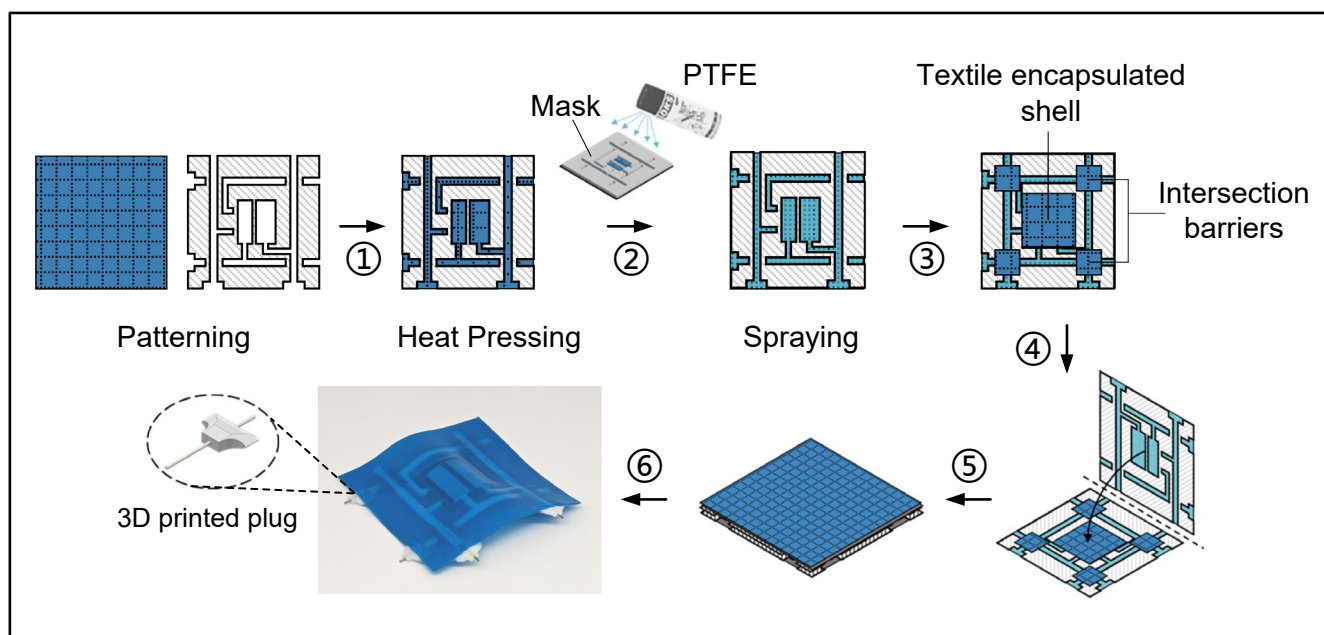
Peer review information *Nature Sensors* thanks Aaron Raymond See, Yifan Wang and the other, anonymous, reviewer(s) for their contribution to the peer review of this work.

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Reprints and permissions information is available at www.nature.com/reprints.

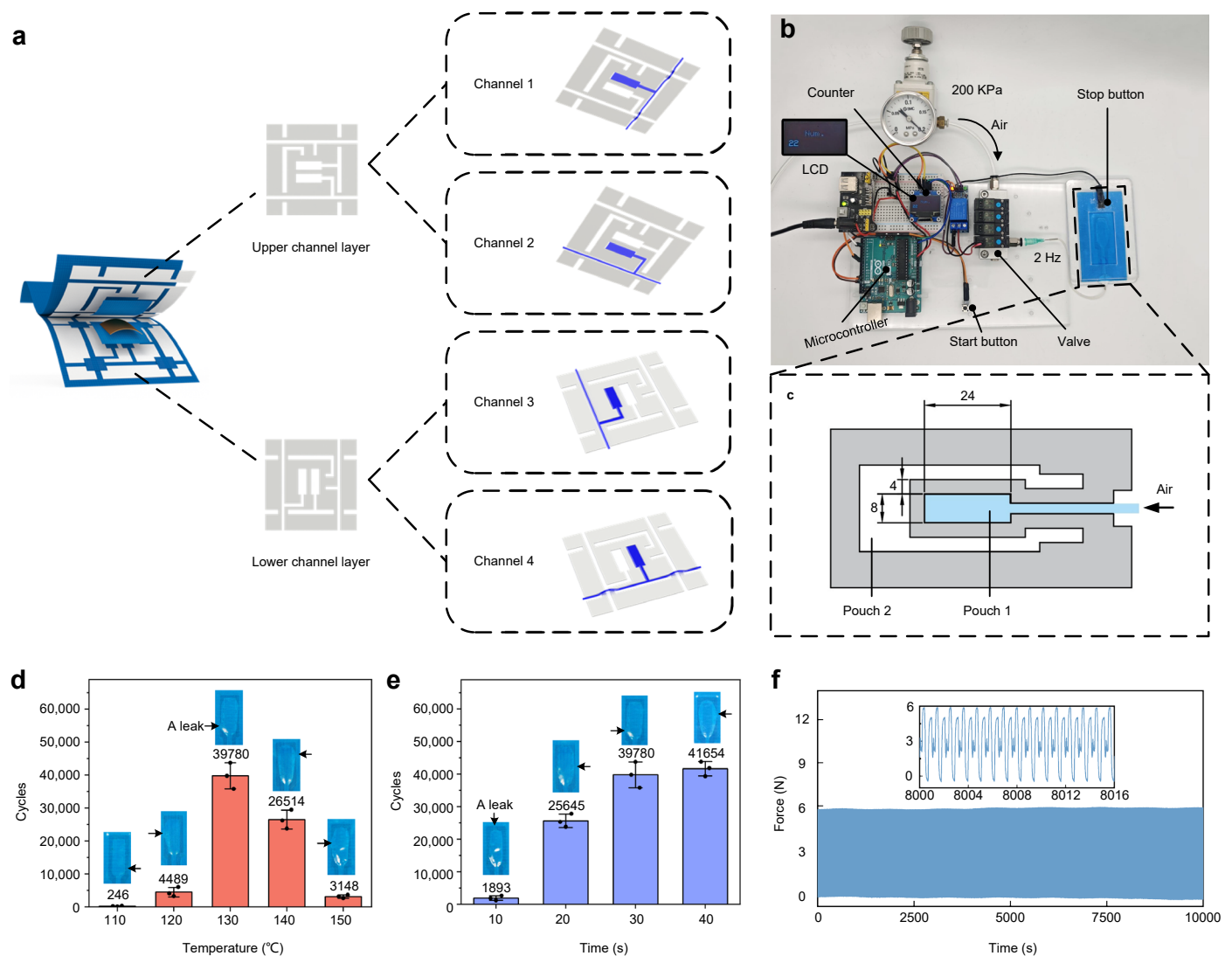
© The Author(s), under exclusive licence to Springer Nature Limited 2026

¹Institute of AI and Robotics, College of Intelligent Robotics and Advanced Manufacturing, Fudan University, Shanghai, China. ²School of Engineering, Westlake University, Hangzhou, China. ³School of Materials Science and Engineering, Zhejiang University, Hangzhou, China. ⁴College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou, China. ⁵Westlake Interactive Robot Technology (Hangzhou) Co. Ltd, Hangzhou, China. ⁶School of Materials Science and Engineering, Shanghai Jiao Tong University, Shanghai, China. ⁷Department of Radiology, Affiliated Hangzhou First People's Hospital, Westlake University School of Medicine, Hangzhou, China. ⁸State Key Laboratory of Cognitive Science and Mental Health, Institute of Psychology, Chinese Academy of Sciences, Beijing, China. ⁹Westlake Institute for Advanced Study, Hangzhou, China. ¹⁰These authors contributed equally: Zhuang Zhang, Sentao Chen, Zihang Yang, Luoqian Emu. ✉ e-mail: hanqing.jiang@westlake.edu.cn

a**b**

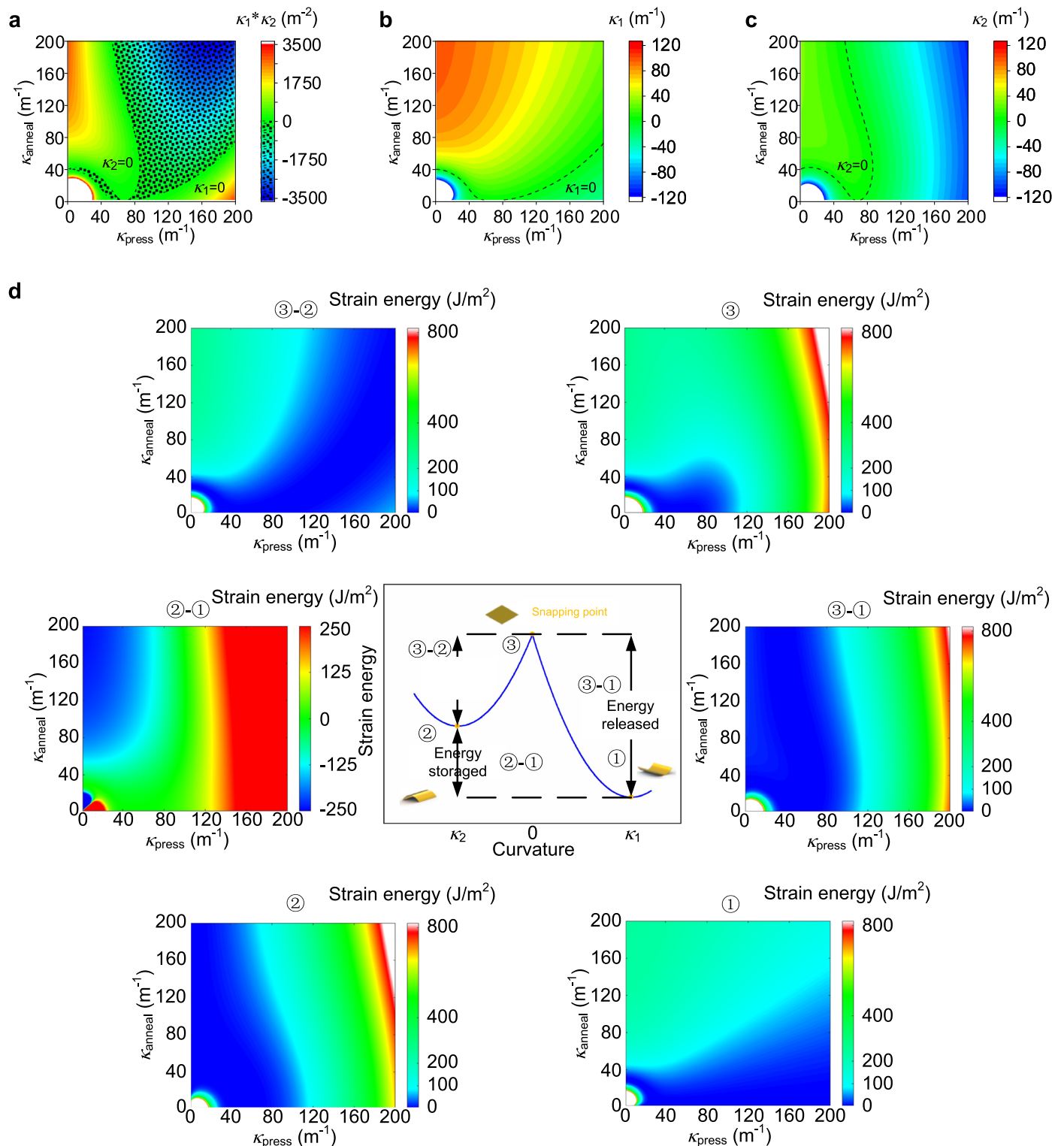
Extended Data Fig. 1 | Fabrication process of the haptic actuator. a, Fabrication process of the textile-encapsulated bistable shell. (Step 1) The beryllium copper (QBe2) sheet was subjected to simultaneous pressing and thermal annealing. (Steps 2–3) The annealed sheet was roll-pressed to reconfigure its curvature. (Step 4) The processed sheet exhibited two distinct stable mechanical states. (Step 5) The bistable shell was sandwiched between two thermoplastic polyurethane-coated (TPU) textile layers (thickness: 0.15 mm). (Step 6) Peripheral thermal bonding was applied to secure the encapsulated structure. **b,** Fabrication process of a shell-integrated pneumatic actuator. (Step 1) Patterned TPU membranes were thermally laminated onto a TPU base layer to construct the air channels. (Step 2) Polytetrafluoroethylene (PTFE) was spray-coated onto the designated

channel regions using a masking technique, ensuring that the air channel integrity remained unaffected during subsequent thermal bonding. (Step 3) Four textile barriers were aligned at the intersection of crossed air channels, dividing the junction into upper and lower compartments. A bistable shell encapsulated with textile was positioned at the centre. (Steps 4–5) Two TPU-coated textile layers, each with embedded air channels, were thermally laminated. The integrated pouch and outer membranes collectively formed two pairs of air bladders arranged in orthogonal layers, one horizontal and one vertical, constituting the actuator's pneumatic network. (Step 6) Four 3D-printed TPU plugs were inserted into the inflation ports to serve as interfaces for PU tubes and were secured via thermal bonding to the textile substrate.



Extended Data Fig. 2 | Structural arrangement and fatigue reliability of pneumatic pouches. **a**, Schematic illustration of four independently controllable airways. Each of the four airways independently controls the inflation of its corresponding pouch. Intersection barriers ensure functional isolation of the airways, even at crossing points. **b**, Experimental setup for cyclic pressurization test. A microcontroller controls solenoid valves to pressurize/depressurize the pouch at a fixed frequency, while an LCD (liquid crystal display) counter displays the number of completed cycles. The system automatically terminates testing upon pouch failure (leakage or rupture), triggered by a pressure-sensitive cutoff switch. **c**, Cross-sectional schematic of the failure detection mechanism. Air leakage from Pouch 1 to Pouch 2 causes the latter

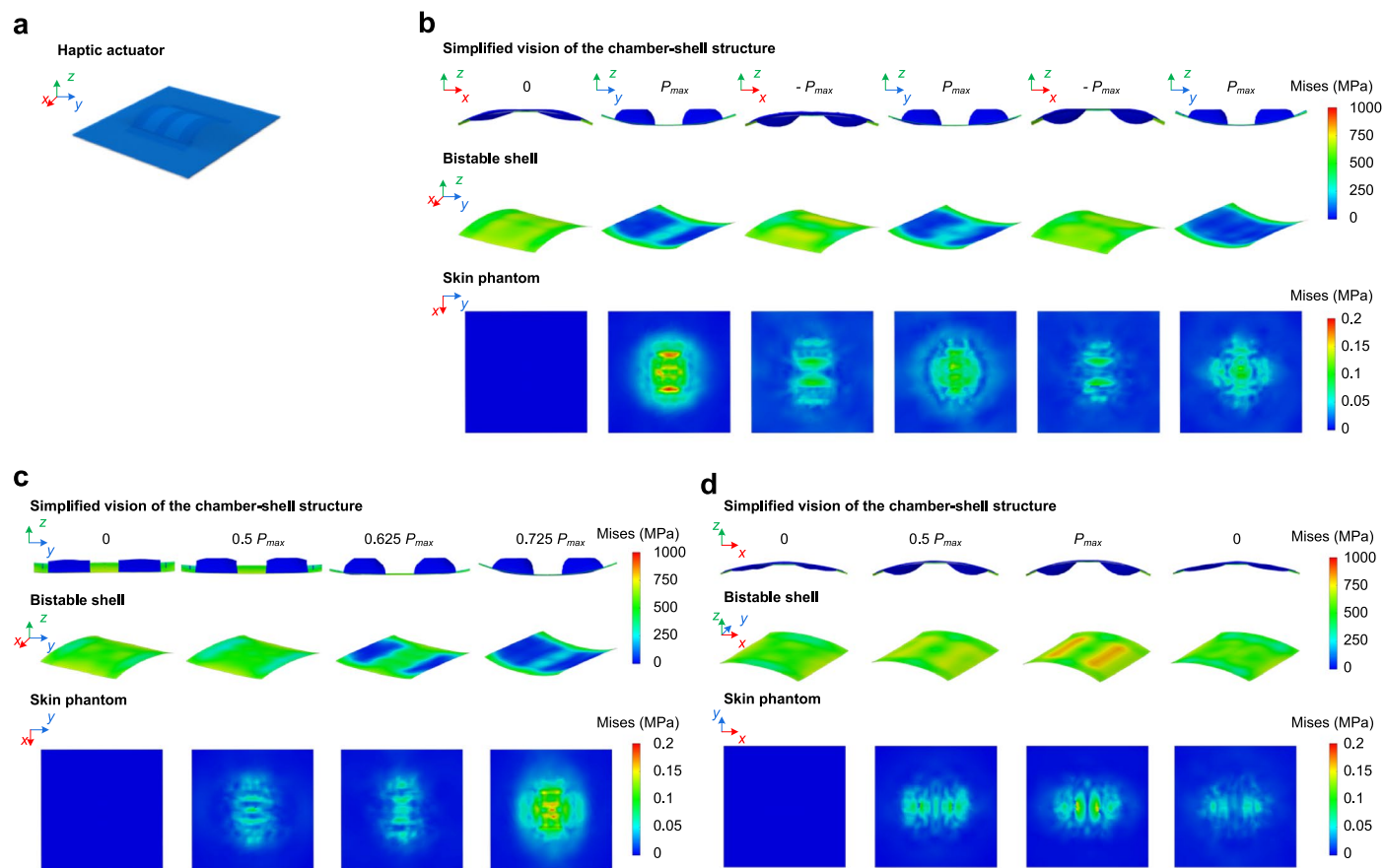
to expand, physically activating an emergency stop button. Dimensions are given in mm. **d** and **e**, Cyclic durability performance of pouches fabricated with different lamination temperatures (Pressure = 200 kPa, Time = 30 s) and durations (Pressure = 200 kPa, Temperature = 130 °C), demonstrating the pouch can withstand over 40,000 cycles under a high input pressure with optimal fabrication parameters (130 °C, 30 s or 40 s). (n = 3 independent samples per condition; data are presented as mean values $\pm$ SD; points, individual samples). **f**, Cyclic performance of the haptic actuator. The actuator was repeatedly actuated between its two mechanically stable states for over 10,000 cycles, with each transition triggered by the snap-through behavior of the bistable shell.



Extended Data Fig. 3 | Influence of initial formation conditions on bistability.

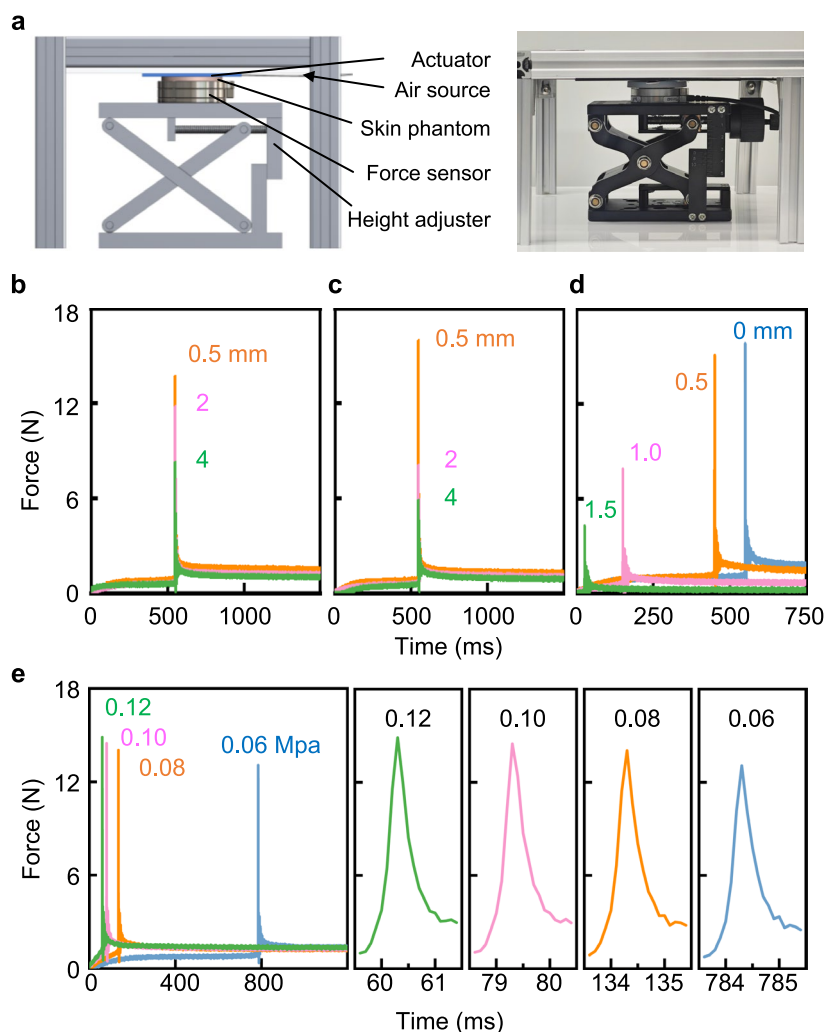
a, Product of the curvatures of the two stable states (κ_1, κ_2) under varying initial formation conditions, which include both thermal annealing and mechanical pressing. As detailed in Supplementary Note 3, bistability requires that curvatures κ_1 and κ_2 have opposite signs. The dotted region highlights the parameter space where this condition is satisfied. **b**, Curvature κ_1 under different formation conditions, with the dotted line indicating zero curvature.

c, Curvature κ_2 under different formation conditions, with the dotted line indicating zero curvature. **d**, Strain energy of the shell as a function of curvature. The central figure illustrates the strain energy and the shape changes of the bistable shell throughout the entire switching process. The six surrounding figures depict the strain energy at the equilibrium states and the energy differences between these equilibrium states under various initial formation conditions.



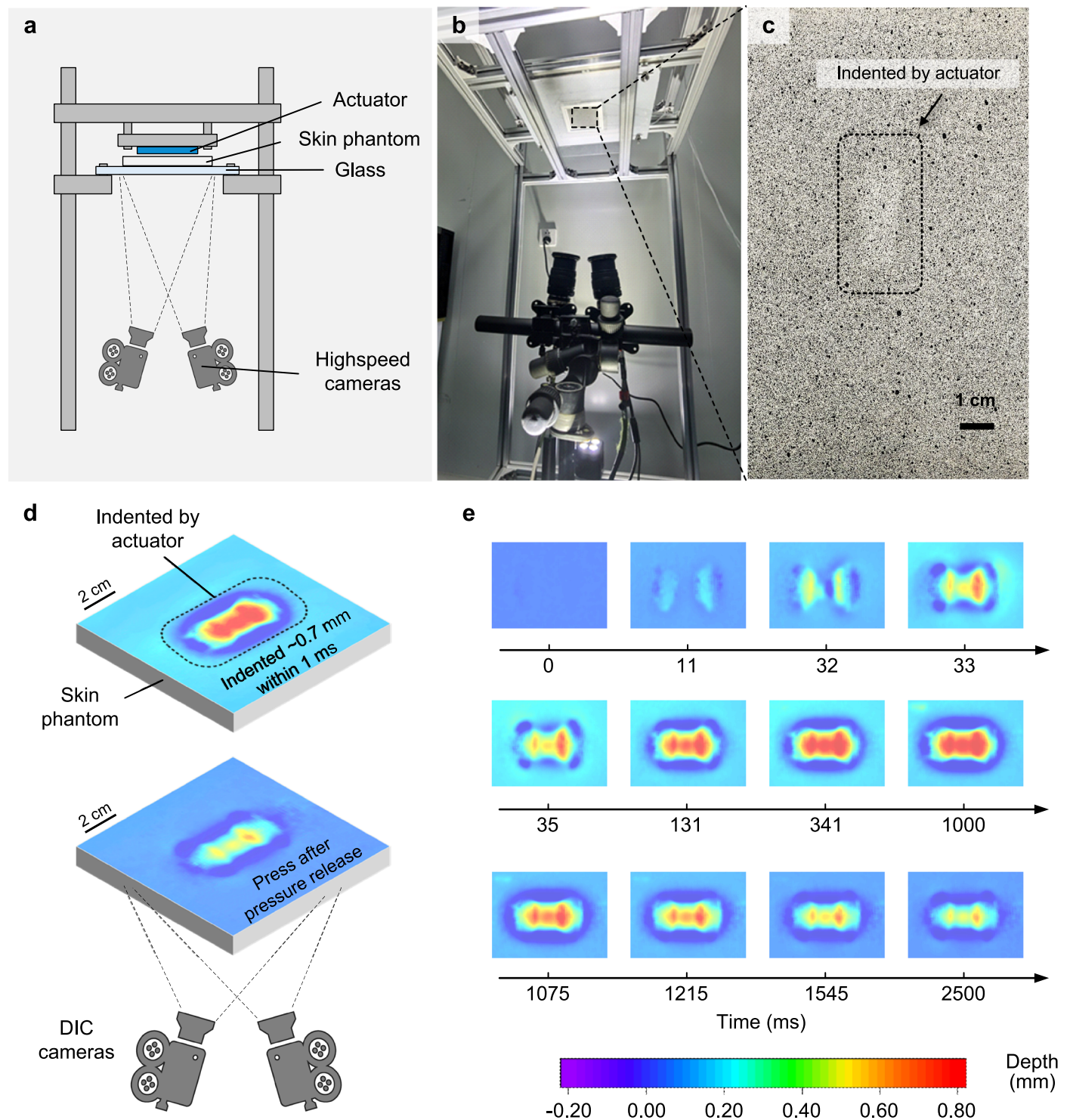
Extended Data Fig. 4 | Finite element analysis (FEA) of stress distribution in the actuator components during various actuation modes. a, Schematic illustration and absolute coordinate of the haptic actuator. **b,** FEA results under

vibration mode. **c,** FEA results under impact mode. **d,** FEA results under press mode. $P_{\max}$ and $-P_{\max}$ denote the preset maximum input pressure of the upper and lower pouches during the simulated actuation process.



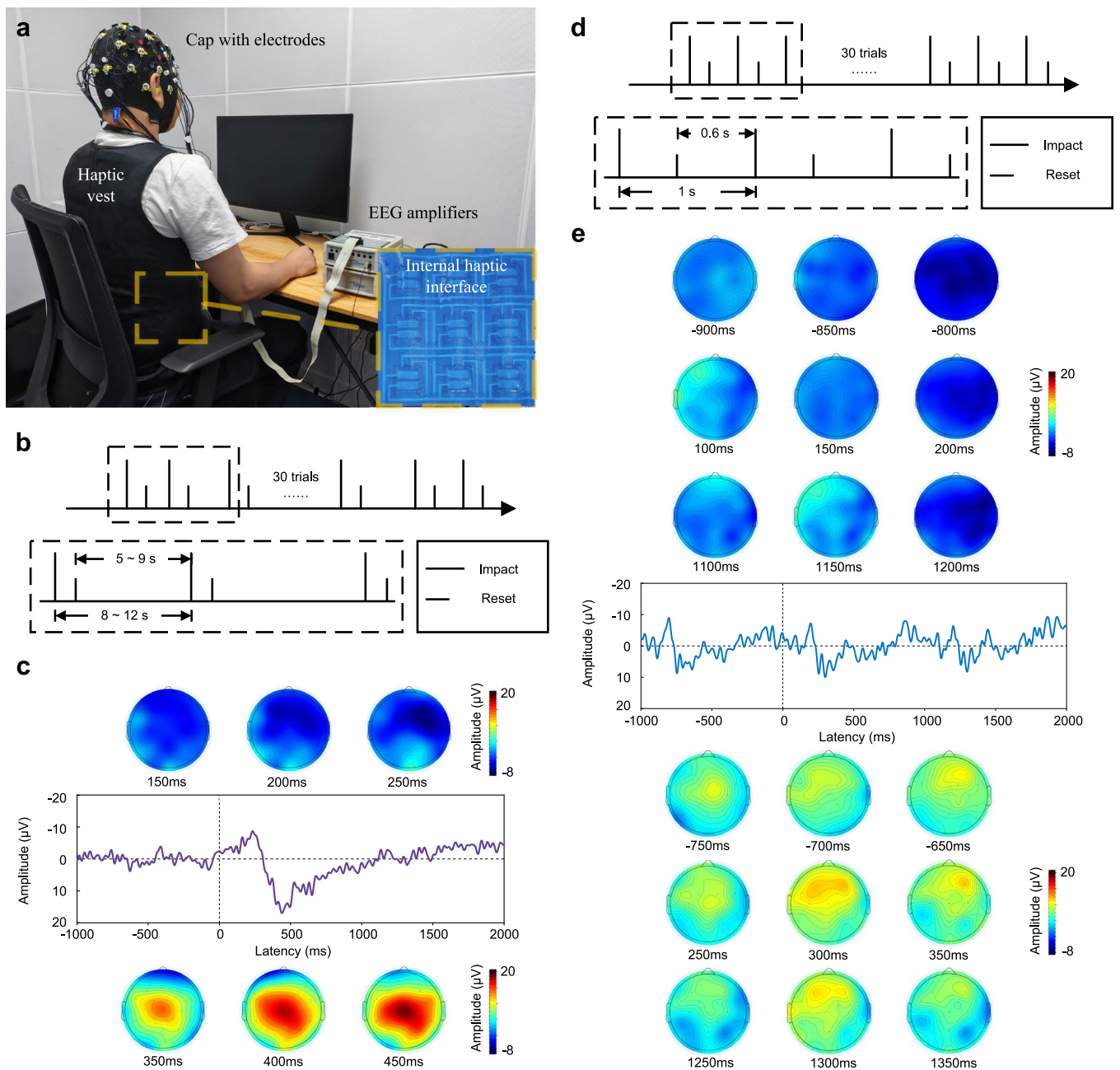
Extended Data Fig. 5 | Mechanical tests of the haptic actuator under impact-mode actuation with varying experimental conditions. a, Schematic diagram and photograph of the mechanical test setup. **b** and **c**, Results of mechanical tests with varying phantom skin materials and thicknesses. Each data was measured three times, and the average data was used. **(b)** Dragon Skin 00-30.

(c) Ecoflex 00-30. **d**, Results of mechanical tests with varying distances between the phantom skin and the haptic actuator. **e**, Enlarged view of the maximum output force under various input pressures. Each data was measured three times, and the average data was used.



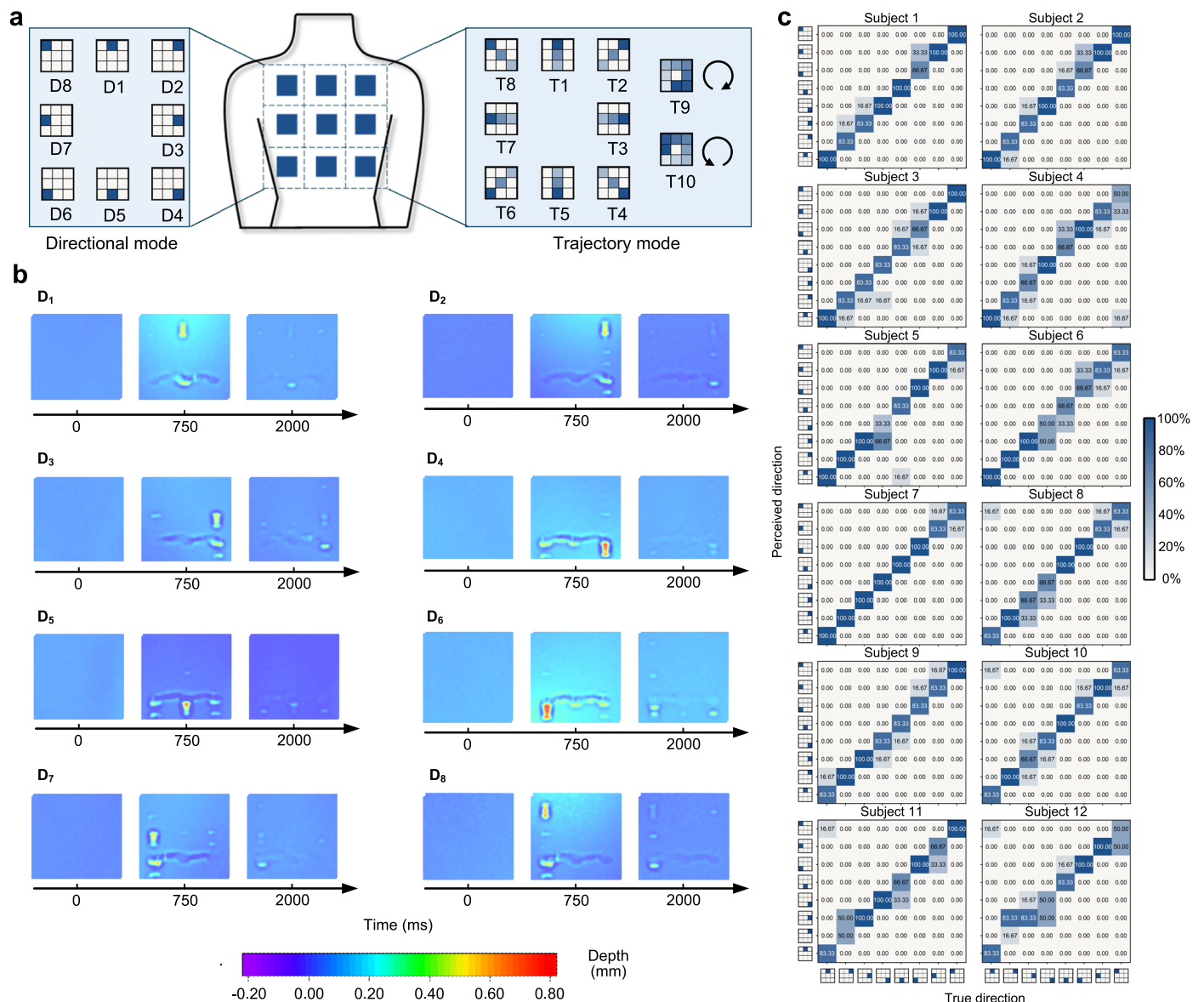
Extended Data Fig. 6 | 3D digital image correlation (DIC) evaluation of out-of-plane deformation on a skin phantom. **a** and **b**, Schematic diagram and photograph of the DIC measurement setup. **c**, Representative frame from an image sequence, showing the applied speckle pattern for displacement tracking. **d**, Schematic diagram of out-of-plane deformation of skin phantoms measured with DIC. **e**, Measured results of out-of-plane deformation on a skin phantom

under impact mode. These results demonstrate that the actuator induces rapid and pronounced deformations on skin phantoms ($E = 61$ kPa), initiating within 1 ms and continuing up to ~ 2.5 ms. The deformation increases under continuous pneumatic pressurization and persists after pressure release at 1000 ms, due to the bistable shell's mechanically stable post-actuation configuration. The results under press and vibration modes are shown in Supplementary Figs. 17 and 18.



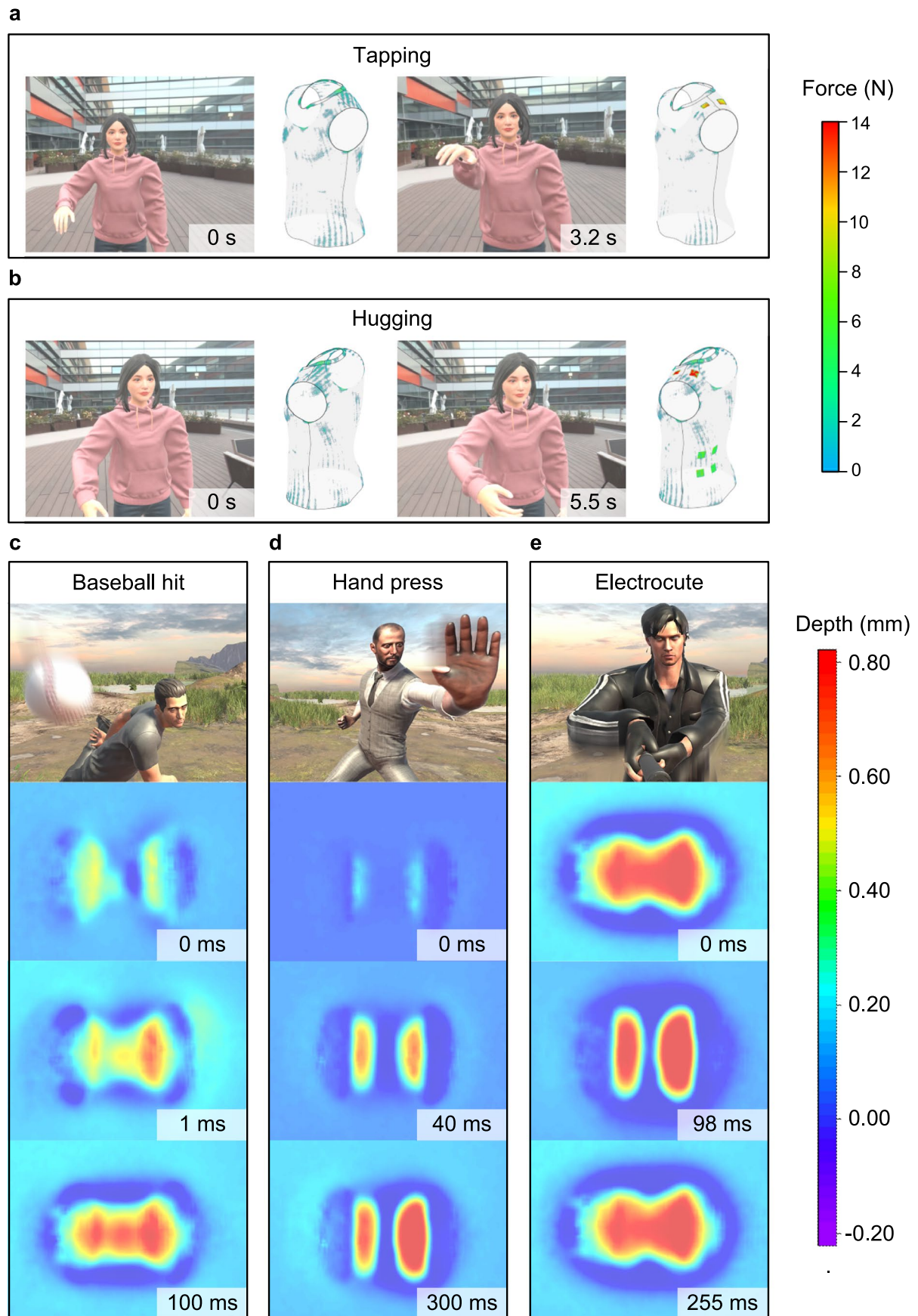
Extended Data Fig. 7 | Electroencephalogram (EEG) measurement and scalp topography analysis. **a**, Experimental setup of the EEG measurement. The participant was seated in a quiet, temperature-controlled, and electro-magnetically shielded room, with no external audio-visual interference. **b** and **c**, Scalp topography dynamics following impact-mode haptic interaction. Impact stimuli were delivered at intervals between 8 to 12 s over 30 trials (**b**). Three seconds after each stimulation, the actuator was reset to its initial state, preparing it for the subsequent trial. Averaged brain potential and scalp topographies (**c**)

under impact stimulation recorded at electrode Cz (nose reference). **d** and **e**, Scalp topography dynamics following vibration-mode haptic interaction. Vibration stimuli were delivered at intervals of 1 s over 30 trials (1 Hz vibration) (**d**). 0.4 s after each triggering of the bistable shell, the actuator was reset to its initial state, preparing it for the subsequent trial. Averaged brain potential and scalp topographies (**e**) under vibration stimulation recorded at electrode Cz (nose reference). Scalp topography dynamics following press mode are shown in Supplementary Fig. 24, with no apparent variation tendency observed.



Extended Data Fig. 8 | Concept and effectiveness of multi-point haptic interactions. a, Haptic language definitions of various directions and trajectories. Eight directions are denoted by symbols in the diagram. D₁-D₈ denote North, Northeast, East, Southeast, South, Southwest, West, and Northwest, respectively. Ten trajectories in accordance with the color-gradient-based symbols. T₁-T₁₀ denote bottom to top, bottom-left to top-right, left to right, top-left to bottom-right, top to bottom, top-right to bottom-left, right to left, bottom-right to top-left, clockwise, and counterclockwise,

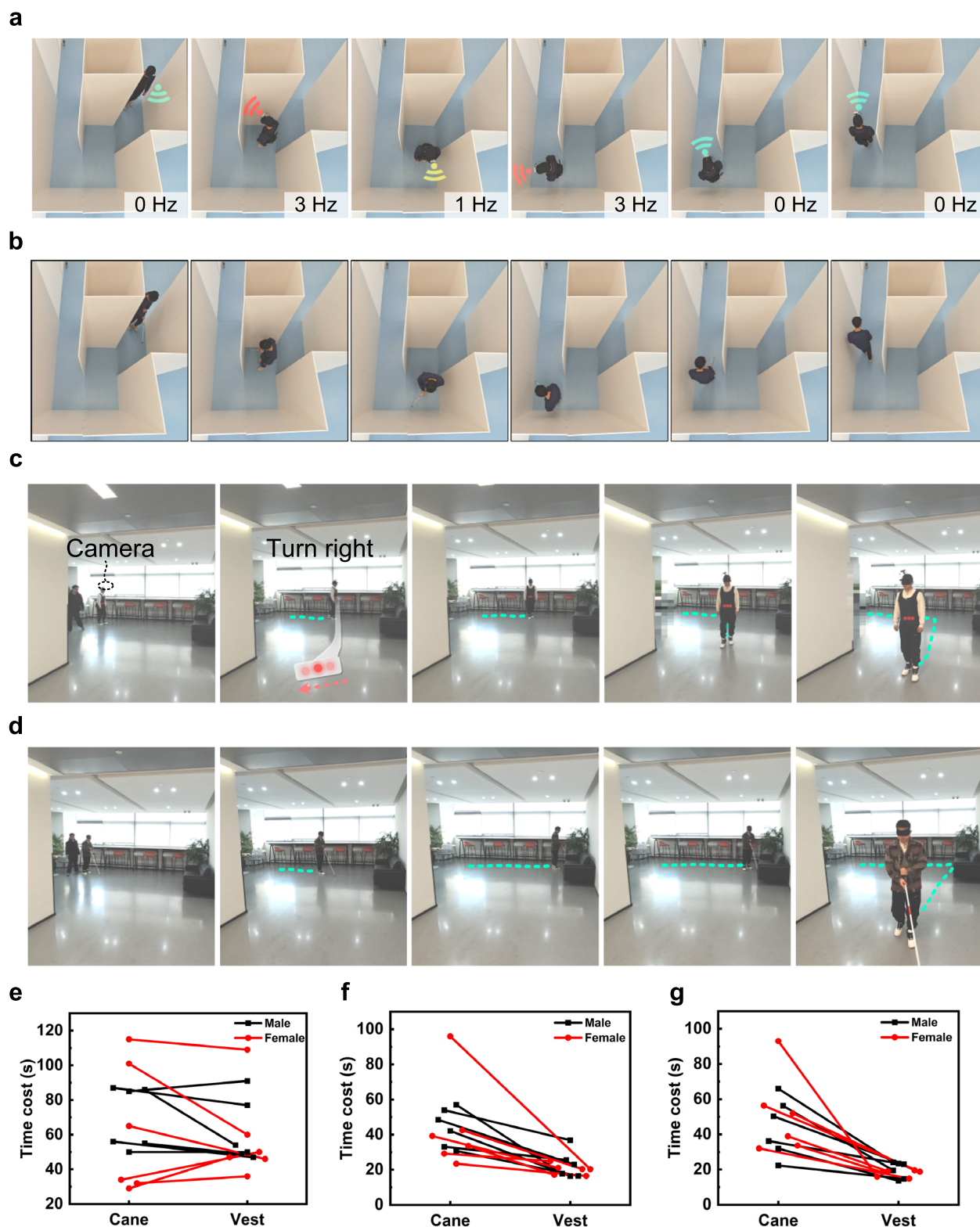
respectively. **b,** Temporal profile of continuous skin phantom's out-of-plane deformation measured by digital image correlation (DIC), under multi-point haptic interactions with eight directions (D₁-D₈). **c,** Confusion matrix showing identification rates of various directions for six male (Subjects 1-6) and six female (Subjects 7-12) participants. Accuracy was averaged over six repeated tests for each subject. The skin phantom's deformation with ten trajectories and the corresponding identification rates are shown in Supplementary Figs. 25-28.



Extended Data Fig. 9 | See next page for caption.

Extended Data Fig. 9 | Sensory replication in VR/AR. a, Haptic replication of a virtual avatar tapping the user's shoulder. A 2 Hz vibration was applied to the user's shoulder from the haptic interface to mimic consecutive taps from the virtual avatar, synchronized with the visual scenario. **b,** Haptic replication of a virtual avatar hugging the user. A press and an impact were applied to the user's waist and shoulder, respectively, via the haptic interface to simulate

the avatar's arm and head during the hug. **c,** Haptic replication of a baseball hit in VR environment, generating a real feeling of hard impact. **d,** Haptic replication of a hand press in VR environment, generating a real feeling of being pushed. **e,** Haptic replication of an electrocute in VR environment, generating a real feeling of continuous vibration.



Extended Data Fig. 10 | Sensory substitution in real world. **a–b**, Video screenshots of a participant walking in the maze. **(a)** Navigation guided by the haptic vest. **(b)** Navigation guided by a white cane. **c–d**, Video screenshots of a participant making decisions under varying path conditions. **(c)** Navigation guided by the haptic vest. **(d)** Navigation guided by a white cane. **e–g**, Completion time for male

and female participants using different navigation strategies. **(e)** Maze task: cane, $P = 0.401$; vest, $P = 0.801$. **(f)** Left-turn task: cane, $P = 0.832$; vest, $P = 0.350$. **(g)** Right-turn task: cane, $P = 0.643$; vest, $P = 0.364$ (independent-samples two-sided t-test; $n = 11$ independent participants; points, individual participants; lines connect paired measurements from the same participant).

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

- | | |
|-------------------------------------|--|
| n/a | Confirmed |
| ☐ | ☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement |
| ☐ | ☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly |
| ☐ | ☒ The statistical test(s) used AND whether they are one- or two-sided
<i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i> |
| ☒ | ☐ A description of all covariates tested |
| ☒ | ☐ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons |
| ☐ | ☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals) |
| ☐ | ☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted
<i>Give P values as exact values whenever suitable.</i> |
| ☒ | ☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings |
| ☒ | ☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes |
| ☒ | ☐ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated |

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	Data were collected using the custom experimental platforms and commercial acquisition systems described in the Methods, including a mixed-reality environment developed in Unity 2022 (Unity Technologies Inc.) with animations prepared in Blender and deployed on Apple Vision Pro and Mac mini, a closed-loop navigation device based on a RealSense D435i camera and Raspberry Pi 5, an ESP32-WROOM-32UE-based control system, an STM32F1C8T6-based response-time measurement setup, a 32-channel EEG acquisition system (BrainCap and BrainAmp, Brain Products GmbH), a binocular high-speed camera system (S1310 with Canon 24-70 mm lens, Revealer), an ATI Mini45 force sensor, a JHY-5000 universal testing machine, and an FSR402 force-sensitive resistor.
Data analysis	Data plots were processed in OriginLab 2021 or with customized programs in MATLAB 2021. Finite-element simulations were performed in ABAQUS, and 3D deformation fields from digital image correlation measurements were reconstructed using RDIC-3D. EEG/ERP data were analyzed using EEGLAB, an open-source MATLAB toolbox. Sample-size estimation was performed using PASS software, and statistical analyses included normality testing and t-tests as described in the Methods.

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

All data generated or analyzed during this study are included in this published article and its Supplementary Information files. The code used for EEG data analysis is available via GitHub at <https://github.com/EMLQ/BHT>.

Research involving human participants, their data, or biological material

Policy information about studies with [human participants or human data](#). See also policy information about [sex, gender \(identity/presentation\), and sexual orientation](#) and [race, ethnicity and racism](#).

Reporting on sex and gender	Sex was recorded and is reported here as male/female counts. The human participant experiments involved four independent groups (n = 12 per group; six males and six females per group), and the EEG experiment involved one healthy 30-year-old male participant. Gender identity was not collected, and no sex- or gender-based subgroup analyses were performed.
Reporting on race, ethnicity, or other socially relevant groupings	Race, ethnicity, and other socially relevant groupings were not collected or used in this study. No analyses were performed using such variables.
Population characteristics	Participants in the human experiments were healthy adults aged 20-35 years. The EEG experiment involved one healthy 30-year-old male participant with no history of chronic pain or neurological disorders.
Recruitment	Participation was voluntary and participants were recruited from Westlake University. All participants provided informed consent before the tests and have no self-selection bias that are likely to impact results.
Ethics oversight	All experiments on human were approved by the Ethics Committee of Westlake University (No. 20231221JHQ001).

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☒ Life sciences ☐ Behavioural & social sciences ☐ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Life sciences study design

All studies must disclose on these points even when the disclosure is negative.

Sample size	Four independent groups of participants were recruited (n = 12 each; six males and six females), with each group assigned to one task. Sample sizes for paired t-tests were estimated using PASS software (alpha = 0.05, power = 0.8) from pilot data (n = 5). Required sample sizes were 9 for the perception task, 4 for the turning task, and 11 for the maze-navigation task; therefore, 12 participants were recruited for each group.
Data exclusions	Data cleansing was performed using boxplot analysis (whiskers = 1.5 IQR), as described in the Methods. One female outlier was excluded from the navigation analyses; therefore, 33 navigation trials from 11 participants were analyzed for Fig. 4k. For the Fig. 3c confusion-matrix aggregation, two participants whose recognition accuracy fell within the statistical outlier interval were excluded, yielding 30 effective trials per mode. No other data were excluded.
Replication	Experimental findings were assessed using repeated trials and repeated measurements as described in the Methods and Supplementary Information. These included repeated human-perception and navigation trials, 30 EEG trials per mode, and cyclic durability testing of the pneumatic pouches, which withstood over 40,000 cycles under high input pressure with n = 3 independent samples per condition. All reported attempts at replication were successful.
Randomization	In the human participant experiments, haptic modes and directional or trajectory cues were presented in individually randomized order for each participant. Randomized inter-trial intervals were also used for the EEG impact and press sessions.
Blinding	Investigator blinding was not applied during data collection because the study focused on device validation and task execution rather than treatment assignment. In randomized perception tasks, participants were not informed in advance of the upcoming haptic mode or cue. Analyses were performed using predefined quantitative procedures.

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☒	☐ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern
☒	☐ Plants

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Plants

Seed stocks

No plants were used in this research.

Novel plant genotypes

No plants were used in this research.

Authentication

No plants were used in this research.