
Supplementary information

Bioelastic state recovery for haptic sensory substitution

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Supplementary Information

Bioelastic state recovery for haptic sensory substitution

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Supplementary Methods

Finite element modeling of electromagnetic and solid mechanical processes

The commercial software packages Ansys and ABAQUS were used for simulation of quasi-magnetostatic and solid mechanical processes respectively. For quasi-magnetostatics, a cylinder was built to represent the solenoid copper coil with 200 turns stranded current excitation. Magnetic force was driven with different currents and separation distance between the solenoidal core and armature. An adaptive mesh (tetrahedron elements) was adopted to ensure computation accuracy. Meanwhile, an axisymmetric model geometry was used for solid mechanical numerical modeling. Four-node bilinear reduced integration elements (CAX4R) and three-node linear elements (CAX3) were applied to different parts according to their geometric complexities. The mesh was highly refined in the indentation area, and convergence was guaranteed for all cases. Rigid body constraints were applied to all metal parts due to their large moduli relative to the skin phantom. Finally, for mechanical response testing of the array, three-node and four-node composite shell elements were used for the polyimide (PI) thin film and copper traces respectively. Eight-node solid elements were used for the electronic components and adhesion layer. Model geometries and boundary conditions for the unit transducer and array are detailed in Extended Data Figs. 3a–3f and Extended Data Figs. 2h–2k respectively. Elastic moduli (E) and Poisson's ratios (ν) were $E_{\text{dragon}} = 15$ MPa and $\nu_{\text{dragon}} = 0.48$ for dragon skin; $E_{\text{resin}} = 2000$ MPa and $\nu_{\text{resin}} = 0.35$ for 3D printed parts; and $E_{\text{PI}} = 2.5$ GPa and $\nu_{\text{PI}} = 0.34$ for polyimide (PI). The fiberglass mesh composite was modeled as a transverse isotropic elastic material with $E_1 = E_2 = 180$ MPa, $E_3 = 0.162$ MPa, $\nu_{12} = 0.48$, $\nu_{13} = \nu_{23} = 0.37$, $G_{12} = 60.8$ MPa and $G_{13} = G_{23} = 102$ MPa. Each skin phantom was modeled as a Mooney–Rivlin hyperelastic material with an initial modulus of 10–400 kPa and a hardening coefficient of 2. Copper was modeled as elastoplastic (without hardening), with $E_{\text{Au}} = 119$ GPa, $\nu_{\text{Au}} = 0.34$, and a yield strain of 0.3%.

The solid mechanical simulation of the kirigami structure consisted of two steps, starting from the fully unfolded state of the two kirigami modules, transitioning to the relaxed state (4.4 mm linear displacement from unfolded), and then transitioning to the compressed state (2 mm translation of the middle platform). The mesh of the skin phantom was refined in the area where it contacts the kirigami, and convergence was guaranteed for all cases. A tie constraint was applied to connect the bottom panel of the upper kirigami structure to the lower kirigami structure, and another tie constraint was applied between the top panel of the upper kirigami structure and the top surface of the armature. The contacting elements were firmly attached to the surface of the skin phantoms using cohesive elements. Extended Data Figs. 3g–3i and their legends detail the model geometries, and boundary conditions for simulation of the kirigami structure with a skin phantom. The elastic modulus (E), Poisson's ratio (ν), and mass density (ρ) were as follows: $E_{\text{skin}} = 5.1$ MPa, $\nu_{\text{skin}} = 0.48$, and $\rho_{\text{skin}} = 1.02$ g/cm³ for the skin phantom; $E_{\text{pet}} = 4000$ MPa, $\nu_{\text{pet}} = 0.4$, and $\rho_{\text{pet}} = 1.54$ g/cm³ for PET plastic; and $E_{\text{pu}} = 7.84$ MPa, $\nu_{\text{pu}} = 0.4$, and $\rho_{\text{pu}} = 1.25$ g/cm³ for polyurethane (PU) plastic.

Spring–mass model of transducer vibration

An analytical model was developed to study the vibration behavior of the transducer, based on the following:

$$m\ddot{x} + kx + c\dot{x} = F, \quad (1)$$

where m is the mass of the transducer (see Extended Data Fig. 3f). Variables k and c are the skin (or skin phantom) stiffness and damping coefficient for relaxed-state vibration, respectively. x is

the indentation depth. F is the magnetic force acting on the plunger (Extended Data Fig. 3f). k is derived based on the slope of indentation curve of skin phantom and F is derived from the corresponding magnetic force to the experimentally measured vibration displacement. Because of the small vibration amplitude, an average magnetic force was used, where F_1 is the average force for positive currents and F_2 is the average force for negative currents. Therefore, the magnetic force can be expanded into a Fourier series:

$$F = \frac{F_1 + F_2}{2} + \frac{2(F_1 - F_2)}{\pi} \left[\sin(\omega t) + \frac{1}{3} \sin(3\omega t) + \frac{1}{5} \sin(5\omega t) + \dots \right], \quad (2)$$

where $\omega = 2\pi f$, and f is the excitation frequency. The steady-state solution of x is

$$x = \frac{F_1 + F_2}{2k} + \sum_{n=1}^{\infty} B_n \sin(\omega_n t - \phi_n), \quad (3)$$

$$B_n \equiv \frac{2}{(2n-1)\pi} \frac{(F_1 - F_2)}{\sqrt{(k - m\omega_n^2)^2 + c^2\omega_n^2}}, \quad (4)$$

where $\omega_n = (2n-1)\omega$ and $\tan \phi_n = c\omega_n/(k - m\omega_n^2)$. There is only one fitting parameter, $\xi = c/(2\sqrt{mk})$, which is the effective damping ratio. In our simulations, $m = 1.1$ g, $k = 570$ N/m, $F_1 = 38$ mN, $F_2 = -24$ mN, and $\xi = 0.5$.

High-speed three-dimensional digital image correlation

Three-dimensional (3D) digital image correlation (DIC), was implemented to accurately quantify the indentation depth and deformation fields induced by the transducer on a skin phantom^{1,2}. This setup, shown in Extended Data Fig. 5, utilized two high-speed cameras (2048×1088 pixel resolution; HT-2000M, Emergent) with 35 mm imaging lenses (F1.4 manual focus; Kowa), operated at 500 Hz. To minimize errors associated with optical paths and camera distortions, both extrinsic and intrinsic camera parameters were optimized including f-number, illumination, focal length, light sensitivity, and gain systems. The 3D imaging acquisition hardware and the transducer system were externally synchronized to allow rapid, automated collection of data for various input powers and operating frequencies. The investigation volume was $20 \times 20 \times 20$ mm³, and RMSE between true calibration and 3D reconstructed points was on the order of 10 μ m. The median values of difference between 66 true calibration points and 3D reconstructed points were ~ 1.6 , 5.2, and 0.1 μ m for x, y, and z coordinates, respectively. To achieve high resolution and accuracy, the DIC subset radius and spacing were set as 10 and 4 pixels, resolving over 1950 grids. Data points with high correlation coefficients (>1.0 max correlation coefficient) were filtered out to minimize errors during the 3D reconstruction process. Filtered data sets were grid-interpolated into 20×20 grid points to generate consistent data points and grid locations across all sets of experiments.

3D DIC was used to measure the spatiotemporal profiles of deformation during vibrotactile stimuli on skin phantoms. The phantoms were uniformly coated with black dots (~ 50 – 200 μ m) using a spray-painting technique. Then, a thin layer of white-pigmented PDMS of identical crosslinker ratio to the phantom was spin-coated on top (500 rpm, 2 minutes) to provide contrast. On a 45:1 PDMS phantom ($E = 43$ kPa), the transducer was driven with $I_{\text{coil-pk}} = 250$ mA and frequencies, 50 Hz, 100 Hz, 150 Hz, and 200 Hz (square waveform). These waveforms were applied in both the relaxed and compressed states (Figs. 3c, 3d and Extended Data Fig. 5). Extended Data Figs. 5g, 5j also shows an example of full-transition vibration, produced by

applying $I_{\text{coil-pk}} = 300$ mA. Supplementary Video 2 shows the deformation fields of representative vibration modes in the spatiotemporal domain.

In addition, 3D DIC was used to evaluate the deformation of a skin phantom (50:1, $E = 31$ kPa) during torsion. The full height of the stacked Kresling modules was 13.6 mm, and the lower module started in the relaxed state at a height of 5 mm (translating 2 mm to the compressed state). Fig. 3l shows the deformation field of the skin phantom when the transducer is in the compressed state. A current amplitude of $I_{\text{coil}} = 500$ mA was applied for transitions to and from the compressed state (2 s and 50 ms pulse durations, respectively). Supplementary Videos 3 and 4 demonstrate the transducer operating under these conditions.

Commercial comparison of vibrotactile stimulus on human subjects

Our methodology for evaluating transducers against benchmark stimuli is adapted from Extended Data Ref. 3. The perceived vibration of our device was evaluated by comparing it with a commercially available linear resonance actuator (LRA; VG0840001D, Vybronic). The LRA allows independent control over amplitude and frequency, making it a comparable benchmark for the vibrotactile modes of our system. This specific unit has a comparable size to ours. The vibration of our transducer was generated in two modes: compressed and relaxed. Our transducer and the LRA were attached to the left and right hands respectively, above the dorsal aspect of the adductor pollicis. The LRA (23.2Ω) was driven with an amplitude of 76 mA and frequencies spanning 50–200 Hz. Our transducer (13.39Ω) was driven at currents ranging from 50–250 mA and frequencies matching the LRA. During 5-second vibration intervals, participants ($n = 12$, six males, six females, ages 20–36) reported whether the vibration felt stronger on their left or right hand. The participants were not given any visual or auditory cues from the transducer. The same stimulus was then repeated, and the participants were asked to rate the intensity of the weaker hand on a scale of 0 to 10, where 10 indicates that the intensities were the same, and 0 indicates they felt no sensation. If the participant reported that the sensation was stronger on the LRA hand, the relative perception of our transducer was calculated as a percentage of their perception of the LRA: (relative perception) = $10\% \times (\text{reported intensity})$. Meanwhile, if the participant reported that they perceived the hand with our transducer more strongly, the score was calculated as (relative perception) = $10\% \times (20 - (\text{reported intensity}))$ (i.e., 0 corresponded to 200% while 10 corresponded to 100%). Samples marked unstable (US) in Supplementary Table 5 refer to cases where the device was monostable under the given conditions or where the given current was sufficient to generate a full transition.

The significance of these results was evaluated using the one-sample t-test with equal variance assumption, given the null hypothesis that the mean is zero. The results of this statistical analysis across $n = 12$ subjects are given in Supplementary Tables 5, 6.

Information-theoretic analysis

The transducer was characterized according to the amount of energy required to transmit a unit of information to the skin. Putting aside aspects such as frequency of vibration and spatial pattern, the transducer can deliver as many as four distinct symbols (illustrated in Fig. 3f). These symbols of information correspond to the compressed (C), relaxed (R), compressed vibration (CV), and relaxed vibration (RV) states. The transducer expends a finite amount of energy, $E_{x \rightarrow y}$, to transition between the compressed and relaxed states, but it only requires a continuous dissipation of power, P_y , when it arrives in the vibration states. In the case where we can approximate that the states arise with a uniform probability distribution, we can define the energy per bit of information as

$$E_b(S) = \frac{\langle \langle E_{x \rightarrow y} \rangle_{x \in S} + P_y t_s \rangle_{y \in S}}{\log_2 |S|}, \quad (5)$$

where t_s is the time interval between symbols, and S is the set of available states. According to the definition of information rate, f_b , the interval can be calculated according to $t_s = \log_2 |S| / f_b$. Since self-transitions do not require energy to establish, we assume $E_{x \rightarrow x} = 0$ for $\forall x$. Also, there is no work associated with a direct transition to a vibration state, $E_{C \rightarrow CV} = 0$ and $E_{R \rightarrow RV} = 0$, and the work associated with an indirect transition follows $E_{R \rightarrow CV} = E_{R \rightarrow C}$ and $E_{C \rightarrow RV} = E_{C \rightarrow R}$. Finally, as previously stated, the compressed and relaxed states do not require continuous dissipation of energy, $P_C = 0$ and $P_R = 0$. Given these parameters, the average energy per bit of information for subsets of Fig. 3f can be calculated according to

$$E_b(\{C, R, CV, RV\}) = \frac{1}{8} (E_{R \rightarrow C} + E_{C \rightarrow R}) + \frac{P_{CV} + P_{RV}}{4f_b}, \quad (6)$$

$$E_b(\{C, R, RV\}) = \frac{2}{9 \log_2(3)} (E_{R \rightarrow C} + E_{C \rightarrow R}) + \frac{P_{RV}}{3f_b}, \quad (7)$$

$$E_b(\{C, R\}) = \frac{1}{4} (E_{R \rightarrow C} + E_{C \rightarrow R}). \quad (8)$$

$$E_b(\{R, RV\}) = \frac{P_{RV}}{2f_b}. \quad (9)$$

The transition energies, $E_{R \rightarrow C} = 4.59$ mJ and $E_{C \rightarrow R} = 111$ mJ, were taken from the average values reported from human measurements in Supplementary Tables 1, 2. The power consumption of the vibration states is based on Ohmic losses for $I_{\text{coil-pk}} = 250$ mA ($P_{CV} = 515$ mW) and $I_{\text{coil-pk}} = 100$ mA ($P_{RV} = 134$ mW) in the compressed and relaxed vibration states respectively, assuming a constant direct-current resistance of $R_{\text{coil}} = 13.39 \Omega$ (mean; 0.384Ω SD; $n = 18$) in the transducer.

A typical commercial vibration can also be described by Eqn. 9. For the LRA used in our perception experiments (VG0840001D, Vybronic), only having on and off states, this calculation simplifies to $E_b(\{\text{ON}, \text{OFF}\}) = P_{\text{LRA}} / (2f_b)$. Since we determined that the perception of vibration was similar for most participants between the relaxed state of our transducer and the LRA at 100 Hz (Extended Data Fig. 7c) and the same power consumption, the entry for $S \in \{R, RV\}$ in Fig. 3g also reflects the characteristics of the LRA ($P_{\text{LRA}} = 134$ mW).

Design principles for the kirigami structure

A Kresling-inspired kirigami structure, fabricated from a series of precisely engineered folds and configurations, can convert linear motion into torsional motion. During the folding process, the distance, h , and rotation angle, θ , between the top and bottom panels follow the relationship,

$$\theta = 2 \sin^{-1} \left(\frac{r}{2} \sqrt{a^2 - h^2} \right), \quad (10)$$

where a is the side length of the unit cell and r is the radius of the circumscribed circle of the hexagonal panel. The challenge in integrating a Kresling structure with our bistable, linear actuator, is that the internal space undergoes significant compression during the folding process, leading to collision. As shown in Extended Data Figs. 6a–6f, folding of the kirigami structure is feasible when the angle α exceeds 90° (α and β are annotated in the figure). To increase the height

of the kirigami structure while keeping the base edge length constant, angle α should approach 90° , with angle β remaining relatively small. To meet these criteria, angles α and β were set to 100° and 30° , respectively. We chose the base edge length of the unit cell to be 6 mm, which achieves relatively small outer dimensions for the kirigami while providing sufficient internal space for the transducer.

The split-crease design was created using the Bézier Curve method. We initially drew two equally long straight creases on the diagonal of the unit cell. As shown in Extended Data Figs. 6a–6f, we used five control points for generating the curve (annotated in the figure): the vertices of the two straight creases (P1 and P5), the midpoint of the top border of the unit cell (P2), the left corner point (P3), and the midpoint of the left border (P4). The curve generated using these rules closely followed the left border of the unit cell, which was not feasible for fabrication. Therefore, we shifted P4 vertically along the normal direction of the drawn curve to P4". Using the new set of control points (P1, P2, P3, P4", P5), the left-curved crease was created.

Choosing the crease length is a tradeoff between the resistance to deformation of the structure and the clearance between the panels and the internal transducer. Extended Data Fig. 6f illustrates a design that avoids collisions, and this was ultimately employed in this study.

Comparing the perception of skin torsion and indentation on human subjects

In this study, a total of 15 healthy participants (7 males, 8 females, ages 23–31 years) were recruited. Two two-tiered torsion units (A and D) and two indentation actuators (B and C) were affixed to the left forearm of each participant (see Extended Data Figs. 7h, 7i). To avoid perception based on actuator location, the indentation and torsion units were alternately positioned at close distances (1 cm). Each stimulus consisted of a single forward and reverse transition within 100 ms. The participants were not given any visual or auditory cues from the transducer. Stimuli from each of the four actuators (illustrated in Extended Data Figs. 7h, 7i) were presented randomly $n = 10$ times, and participants reported whether they perceived indentation or vibration. Accuracy was averaged over 15 subjects with 10 repeated trials ($n = 150$). Raw data and results can be found in Supplementary Table 14 and Extended Data 7i respectively.

Comparing the perception of skin torsion at multiple locations on human subjects

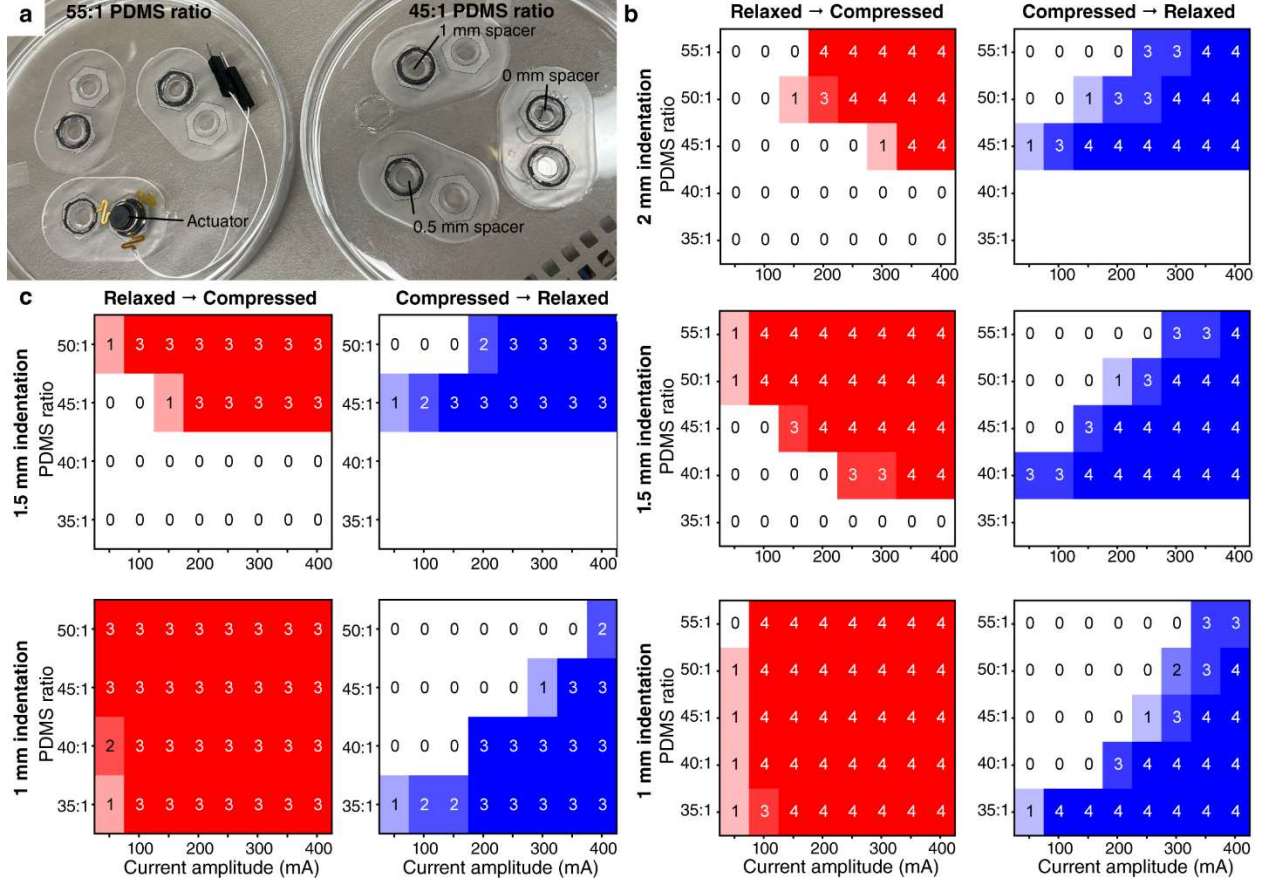
This study involved 12 healthy participants (7 males, 5 females, ages 23–31). Three two-tiered torsion units were mounted on the left forearm of each participant, with locations labelled as A, D, and E in Extended Data Figs. 7h, 7j. Each stimulus consisted of a single forward and reverse transition within 100 ms. The participants were not given any visual or auditory cues from the transducer. Four patterns of simultaneous stimuli, illustrated in Extended Data Figs. 7h, 7j, were presented randomly $n = 10$ times, and participants reported which pattern they perceived. The purpose of this experiment was to determine the ability of the participants to distinguish patterns of simultaneous torsion. The first pattern, P1, consisted of three units (A, D, and E, as indicated in Extended Data Fig. 7j). The other three patterns, P2, P3, and P4, consisted of the first pattern with one of the units removed. In the context of the pattern defined by P1, one of the key behaviors this experiment evaluated was whether removal of one unit would elicit a similar enough perception that it would be mistaken for the original pattern. This experiment also evaluated how well the participants could discriminate between each of those 2-unit patterns (P2, P3, and P4). Individual results are shown in Supplementary Fig. 7 and Supplementary Table 15. Accuracy was averaged over 12 subjects with 10 repeated trials ($n = 120$). Summarized results are reported in Extended Data Fig. 7j.

Cyclic mechanical testing of the haptic array and unit transducers

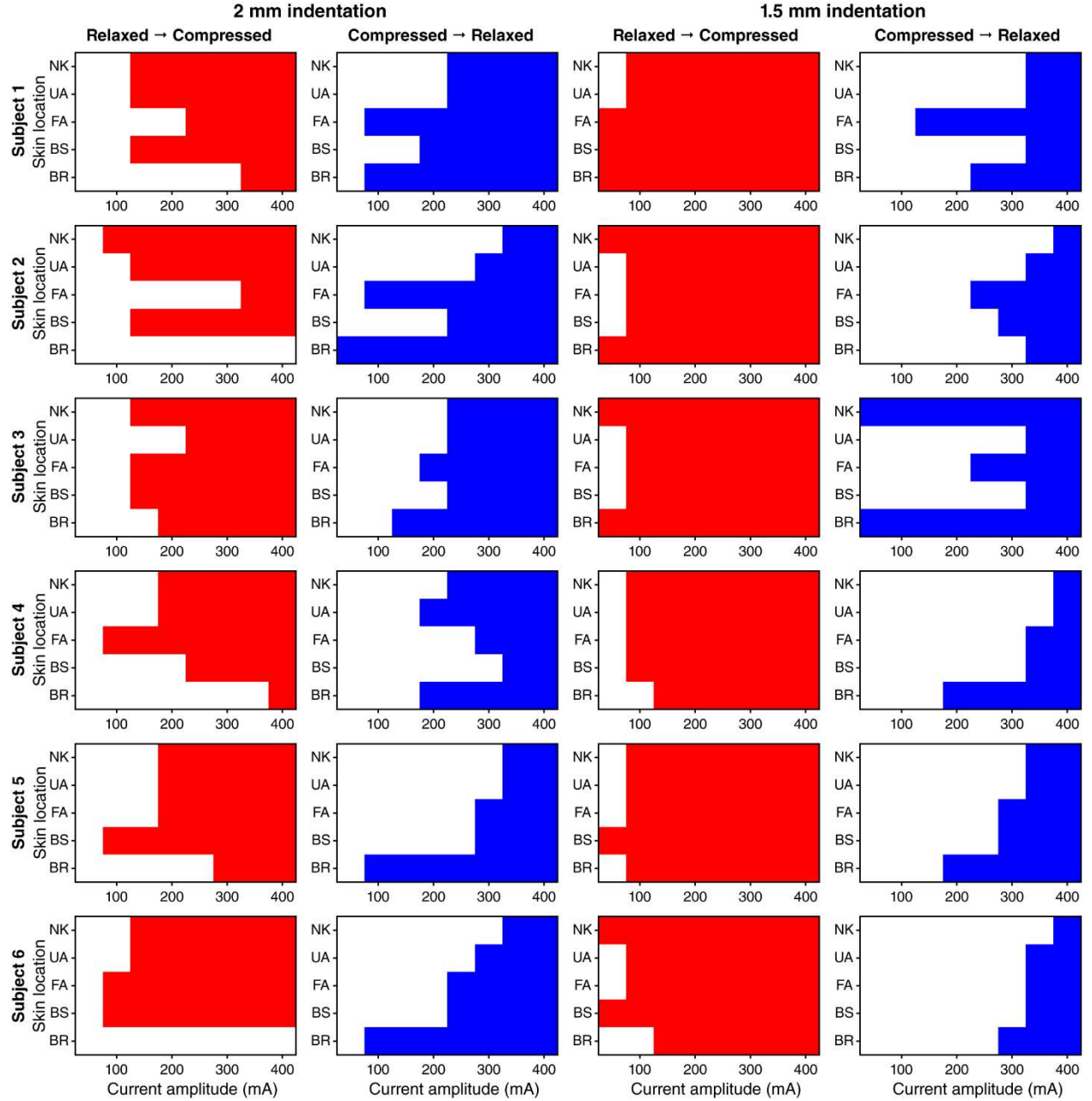
The durability of the integrated haptic array with 19 transducers was interrogated by affixing it to an elastomeric substrate (Ecoflex). Armatures were removed to accommodate the substrate. The substrate's two ends were secured to a motorized stretching machine. Device bending was induced by narrowing the gap between the clamps, calculating the bending radius from a side view of the device and substrate (see Extended Data Fig. 2h). Stretching (18%) was achieved by widening the gap between the clamps, calculating relative stretching based on the distance between actuators (see Extended Data Fig. 2j). The functionality of each transducer was monitored *in situ* by the embedded inductance measurement unit, periodically transmitting during cyclic stretching and bending (1,000 cycles; see Extended Data Fig. 2l).

The durability of the kirigami structure was evaluated by adhering a unit cell to a skin phantom ($E = 31$ kPa). As shown in the inset to Extended Data Fig. 2m, a test fixture was mounted onto the upper panel of the kirigami structure and onto the diametrically opposing surface of the skin phantom. The rotation angle of the lower ring of the structure against the phantom was monitored periodically while driving linear translation along the longitudinal axis of the structure using the test fixture (20,000 consecutive cycles; 3 mm translation; 8.5 mm initial height). See Extended Data Fig. 2m for additional details and results.

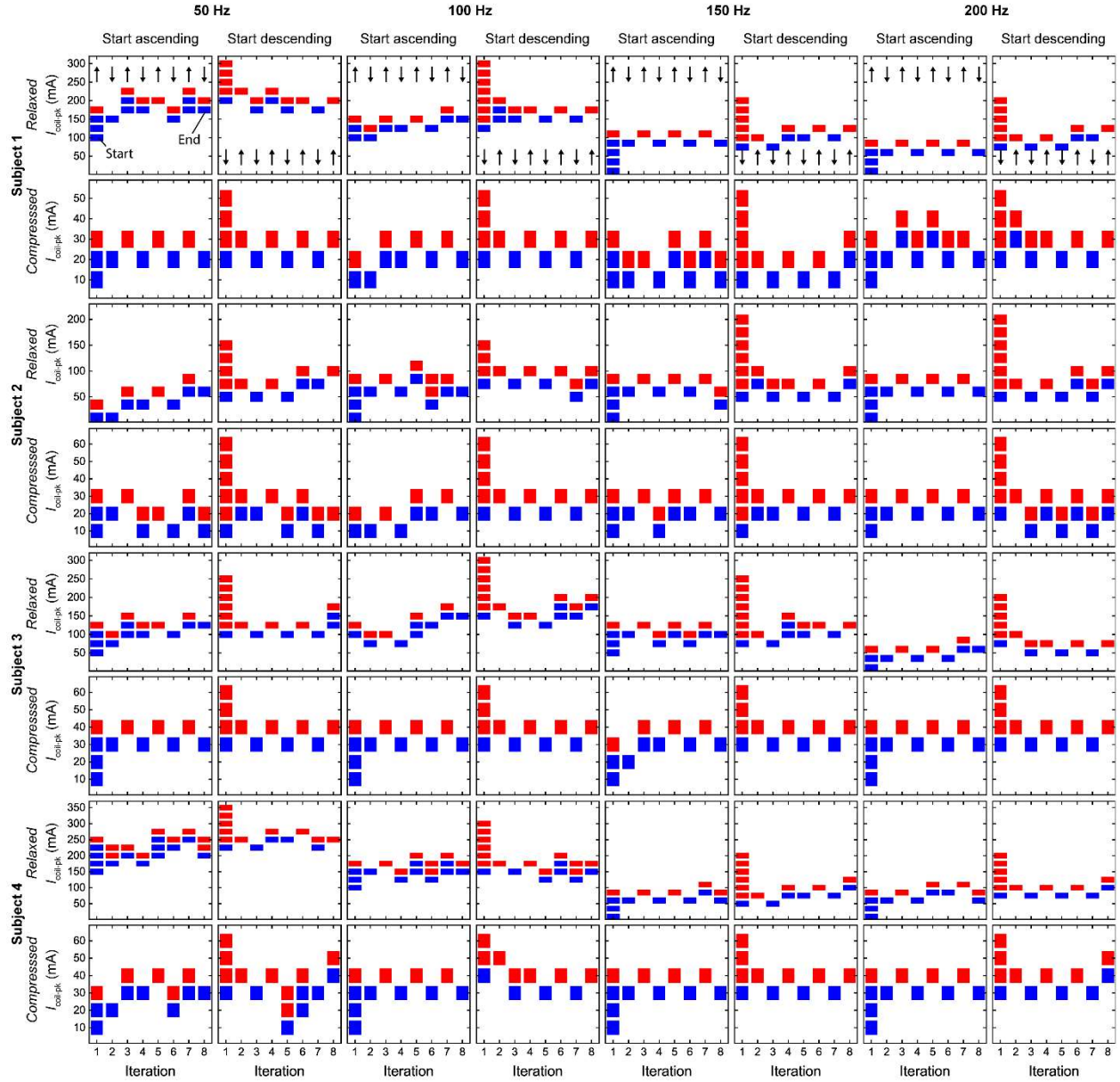
Finally, the durability of the unit transducer was evaluated by performing bistability measurements according to the procedures defined in the Methods section. The asterisk in Fig. 2d indicates conditions ($E = 43$ kPa; $h = 5$ mm) where 120,000 consecutive transitions were performed successfully over a 96-hour period.



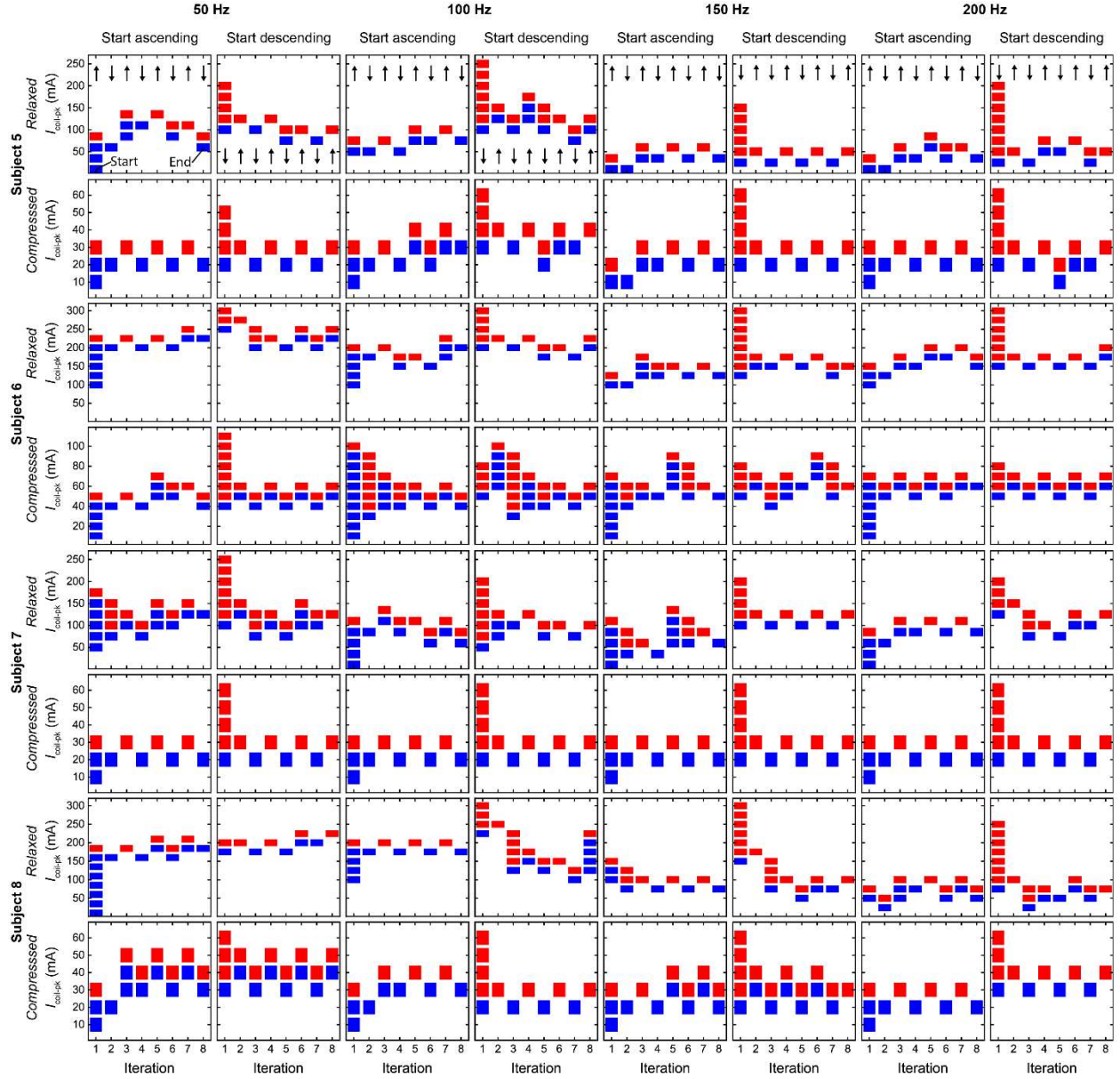
Supplementary Fig. 1. Bistability measurements on skin phantoms. **a** Experimental setup for bistability evaluation, indicating skin phantoms (5 mm), harness variants, and a transducer. **b** Evaluation of bistability on skin phantoms with varying currents and crosslinker ratios for phantom thickness $d = 5$ mm. The heatmap shades correspond to the number of transducers (out of $n = 4$) that successfully transitioned under the given condition. The red column corresponds to the transition from relaxed to compressed, and the blue column corresponds to transition from compressed to relaxed. Each row corresponds to effective indentation (adjusted with harness variants). **c** Evaluation of bistability on skin phantoms with varying currents and crosslinker ratios for phantom thickness $d = 2$ mm ($n = 3$).



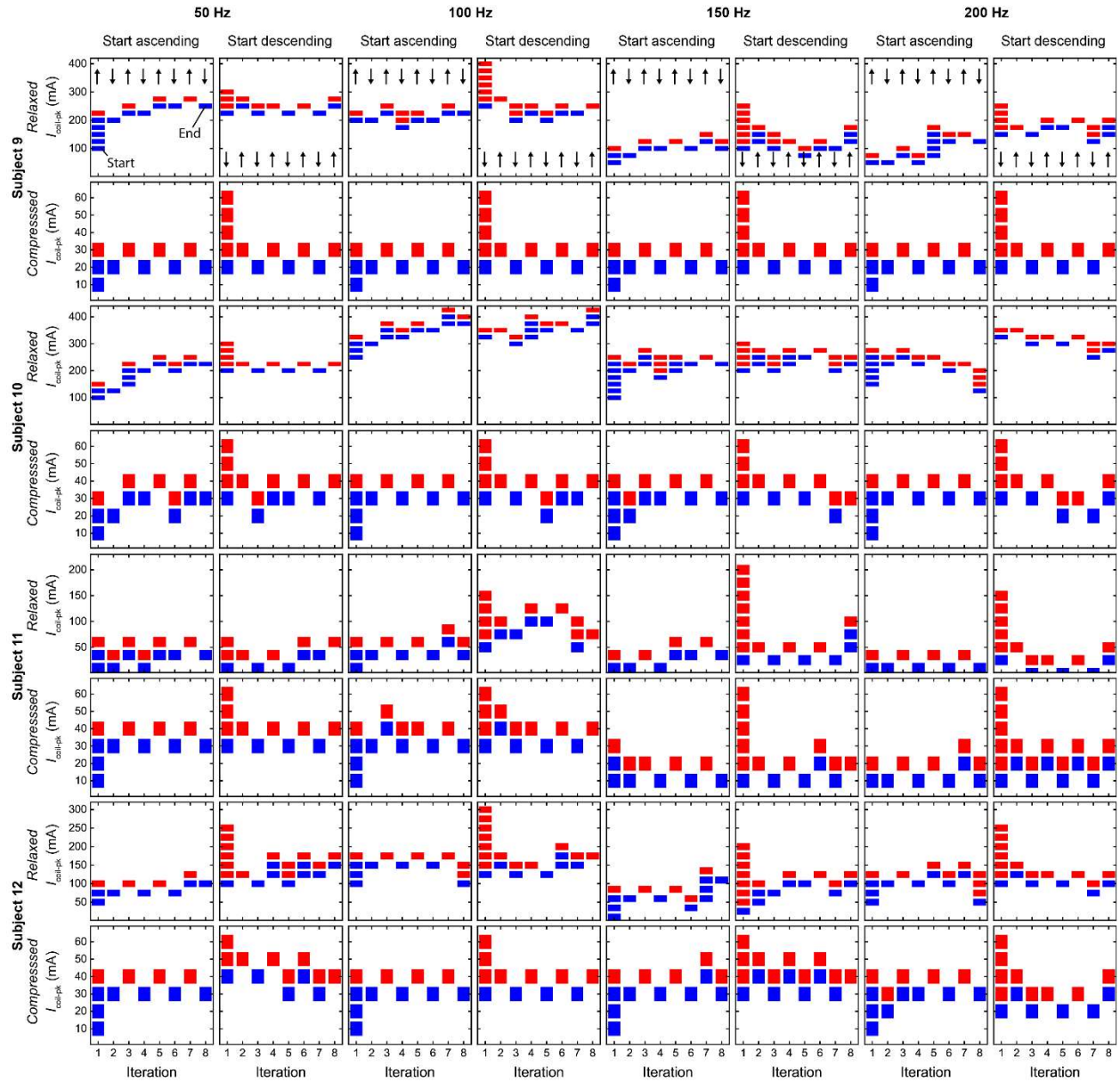
Supplementary Fig. 2. Bistability measurements on human subjects. Evaluation of bistability for $n = 6$ subjects on the dorsal aspect of the neck near the C6 and C7 vertebrae (NK), dorsal aspect of upper arm (UA), ventral forearm (FA), dorsal palm on adductor pollicis (BS), and dorsal palm on metacarpal III (BR) with 1.5 mm and 2 mm effective indentations (Subject 1, male, age 36; Subject 2, male, age 30; Subject 3, male, age 23; Subject 4, female, age 20; Subject 5, female, age 20; Subject 6, female, age 24). The red column corresponds to the transition from relaxed to compressed, and the blue column corresponds to transition from compressed to relaxed.



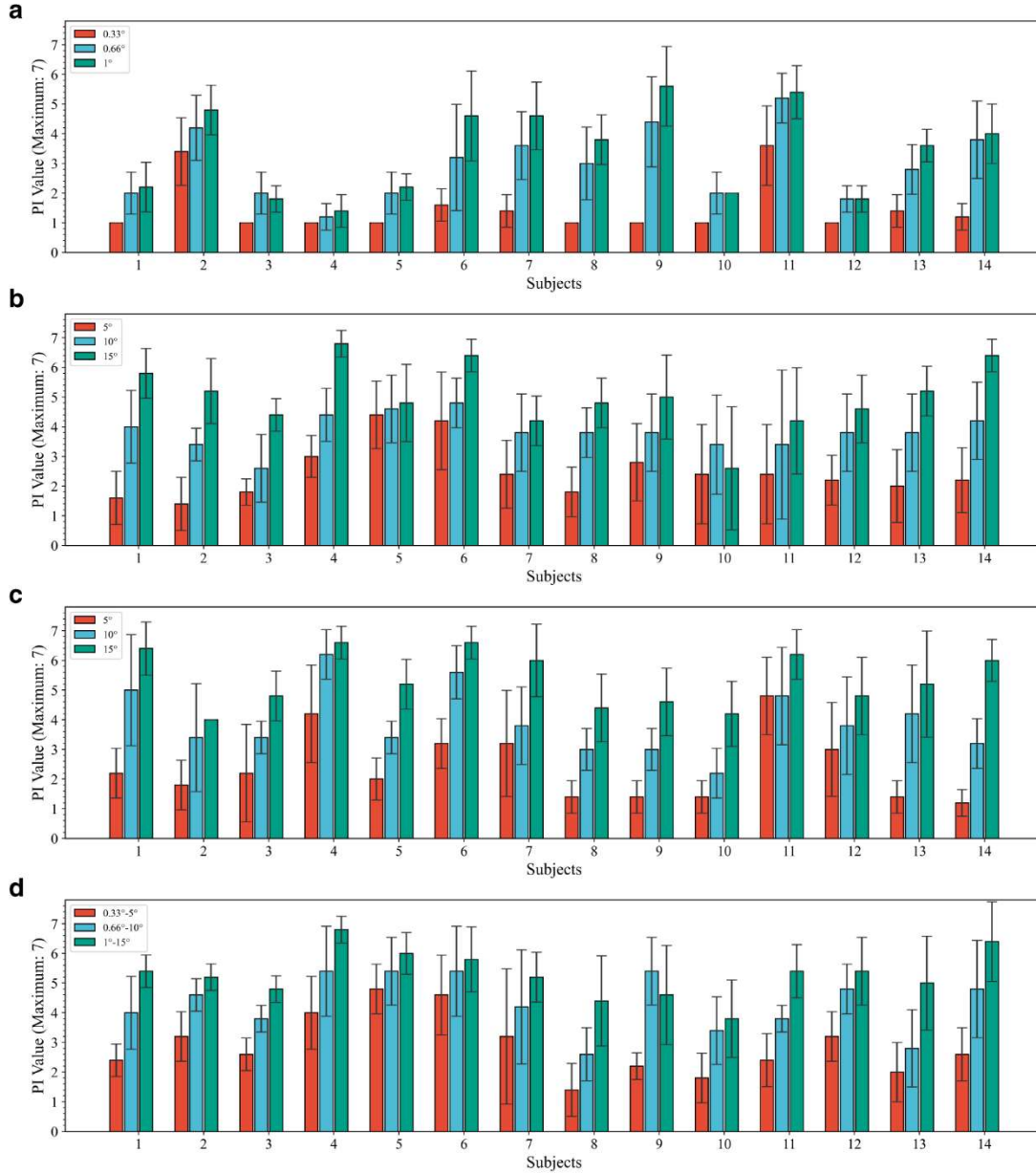
Supplementary Fig. 3. Current amplitudes from which vibration perception threshold were derived for Subjects 1–4. Each block plotted above represents one trial of the adaptive staircase, where red and blue indicate “yes” and “no” respectively for each given current ($I_{\text{coil-pk}}$). The height of each block corresponds to the step size for each trial. Iterations alternate between ascending (starting below threshold and increasing until receiving “yes”) and descending (starting above threshold and decreasing until received “no”). Columns labelled “Start ascending” indicate that Iteration 1 and other odd-numbered iterations in that column are ascending. Columns labelled “Start descending” indicate that Iteration 1 and other odd-numbered iterations in that column are descending. For each combination of state and frequency, trials would start with the first trial in Iteration 1 (“Start ascending” column) and, immediately after, the first trial of Iteration 1 (“Start descending” column). The trials would then alternate back and forth (interleaved) between these columns in the order dictated by the direction (ascending or descending) of each subsequent iteration (Iterations 1–8). Participants: Subject 1, male, age 36; Subject 2, female, age 23; Subject 3, male, age 25; and Subject 4, female, age 28.



Supplementary Fig. 4. Current amplitudes from which vibration perception threshold were derived for Subjects 5–8. Each block plotted above represents one trial of the adaptive staircase, where red and blue indicate “yes” and “no” respectively for each given current ($I_{\text{coil-pk}}$). The height of each block corresponds to the step size for each trial. Iterations alternate between ascending (starting below threshold and increasing until receiving “yes”) and descending (starting above threshold and decreasing until received “no”). Columns labelled “Start ascending” indicate that Iteration 1 and other odd-numbered iterations in that column are ascending. Columns labelled “Start descending” indicate that Iteration 1 and other odd-numbered iterations in that column are descending. For each combination of state and frequency, trials would start with the first trial in Iteration 1 (“Start ascending” column) and, immediately after, the first trial of Iteration 1 (“Start descending” column). The trials would then alternate back and forth (interleaved) between these columns in the order dictated by the direction (ascending or descending) of each subsequent iteration (Iterations 1–8). Participants: Subject 5, female, age 20; Subject 6, female, age 20; Subject 7, male, age 29; and Subject 8, female, age 35.

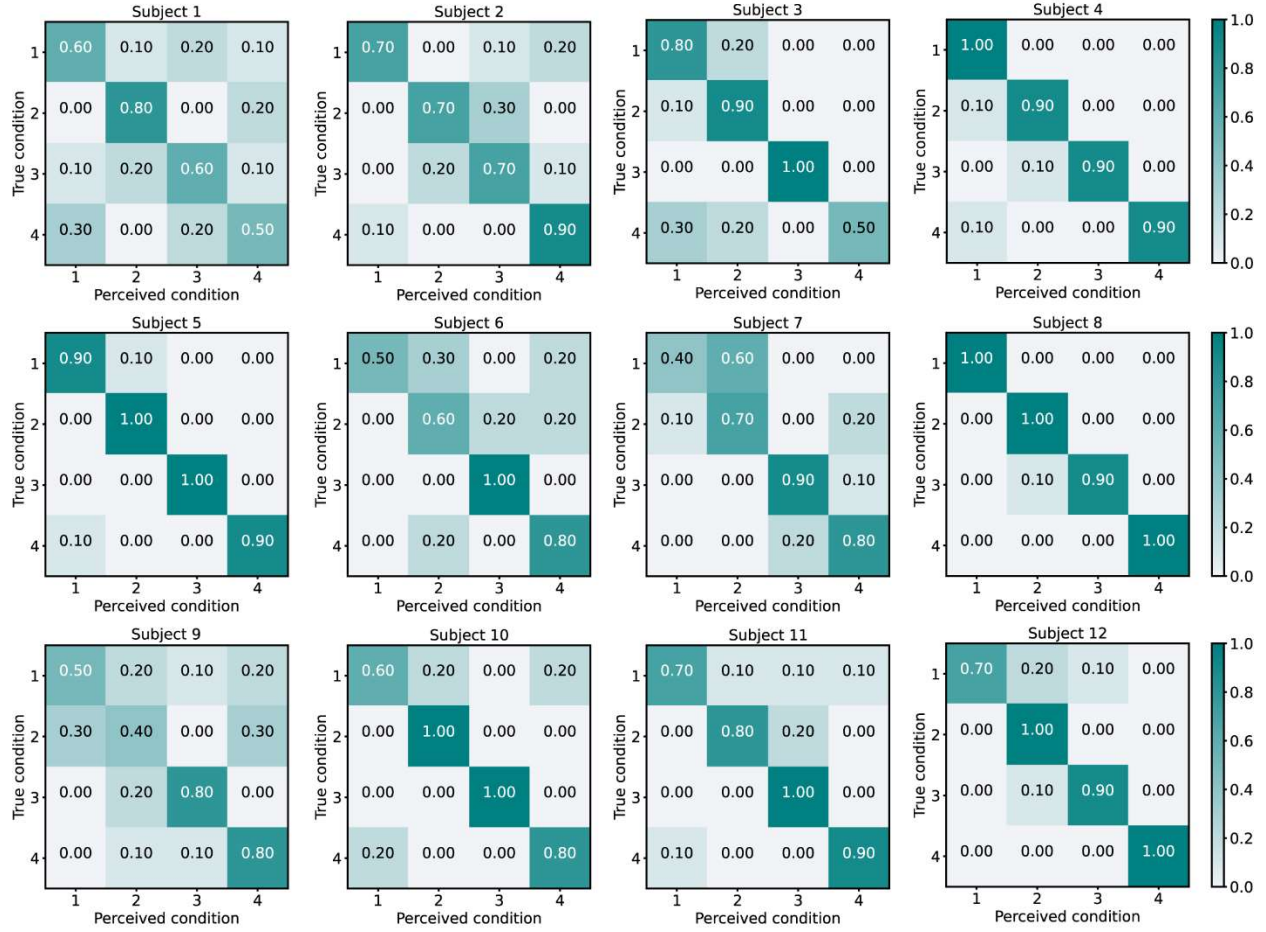


Supplementary Fig. 5. Current amplitudes from which vibration perception threshold were derived for Subjects 9–12. Each block plotted above represents one trial of the adaptive staircase, where red and blue indicate “yes” and “no” respectively for each given current ($I_{\text{coil-pk}}$). The height of each block corresponds to the step size for each trial. Iterations alternate between ascending (starting below threshold and increasing until receiving “yes”) and descending (starting above threshold and decreasing until received “no”). Columns labelled “Start ascending” indicate that Iteration 1 and other odd-numbered iterations in that column are ascending. Columns labelled “Start descending” indicate that Iteration 1 and other odd-numbered iterations in that column are descending. For each combination of state and frequency, trials would start with the first trial in Iteration 1 (“Start ascending” column) and, immediately after, the first trial of Iteration 1 (“Start descending” column). The trials would then alternate back and forth (interleaved) between these columns in the order dictated by the direction (ascending or descending) of each subsequent iteration (Iterations 1–8). Participants: Subject 9, male, age 24; Subject 10, male, age 26; Subject 11, female, age 29; and Subject 12, male, age 33.



Supplementary Fig. 6. Individual outcomes for perceptual intensity of torsional structures. Perceptual intensity evaluated according to its definition in the Methods section for $n = 14$ human participants (8 males, 6 females, ages 23–31) under variations in indentation and torsion of the ring and disk structures (bars, mean values over 5 repeat measures; whiskers, standard deviation). **a** Outcomes reported for rotation and indentation of ring, in which the ring was rotated to angles of 0.33°, 0.66°, and 1° with a static indentation of 0.2 mm. A statistically significant difference can be seen within this ring–disk configuration ($p < 0.0001$, Friedman test). **b** Outcomes reported for rotation of disk, in which the disk was rotated to angles of 5°, 10°, and 15° with a static indentation of 0 mm. According to the Friedman test, a statistically significant difference can be seen within this ring–disk configuration ($p < 0.0001$). **c** Outcomes reported for rotation and indentation of disk, in which the disk was rotated to angles of 5°, 10°, and 15° with a static indentation of -0.4 mm. A statistically significant difference can be seen within this ring–disk configuration ($p < 0.0001$, Friedman test). **d** Outcomes reported for rotation and indentation of

rink and disk, in which the ring and disk were rotated to angles of (0.33°, 5°), (0.66°, 10°), and (1°, 15°) with a static indentation of (0.2 mm, −0.4 mm). A statistically significant difference can be seen within this ring–disk configuration ($p < 0.0001$, Friedman test).



Supplementary Fig. 7. Individual outcomes for torsion pattern discrimination. Accuracy was averaged over 10 repeated measures for each subject (7 males, 5 females, ages 23–31). Notable individual differences in tactile perception were observed.

Supplementary Table 1

Mechanical bistability evaluation in clinical samples of healthy individuals (Subject 1, male, age 36; Subject 2, male, age 30; Subject 3, male, 23). Measurements were performed in three skin locations. The absolute value of current and pulse duration required to transition the armature between indented and closed states was measured for $n = 6$ participants. The indentation depth was adjusted by performing experiments with harnesses of varying heights. The skin was preconditioned by indenting it for 30 s before each transition.

		2 mm indentation		1.5 mm indentation	
		Rel. → Com.	Com. → Rel.	Rel. → Com.	Com. → Rel.
Subject 1	Forearm	200 mA	400 mA	100 mA	400 mA
		10 ms	20 ms	10 ms	60 ms
		5.36 mJ	4.28 mJ	1.34 mJ	129 mJ
	Dorsal hand (MIII)	150 mA	400 mA	100 mA	400 mA
		20 ms	40 ms	10 ms	80 ms
		6.06 mJ	85.7 mJ	1.34 mJ	171 mJ
	Dorsal hand (AP)	100 mA	400 mA	100 mA	400 mA
		10 ms	20 ms	10 ms	80 ms
		1.34 mJ	42.8 mJ	1.34 mJ	171 mJ
Subject 2	Forearm	150 mA	300 mA	100 mA	400 mA
		10 ms	20 ms	10 ms	80 ms
		3.01 mJ	24.1 mJ	1.34 mJ	171 mJ
	Dorsal hand (MIII)	X	X	100 mA	400 mA
				10 ms	100 ms
				1.34 mJ	214 mJ
	Dorsal hand (AP)	200 mA	400 mA	100 mA	X
		10 ms	10 ms	10 ms	
		5.36 mJ	21.4 mJ	1.34 mJ	
Subject 3	Forearm	100 mA	400 mA	50 mA	X
		40 ms	60 ms	10 ms	
		5.36 mJ	129 mJ	0.335 mJ	
	Dorsal hand (MIII)	100 mA	400 mA	100 mA	X
		40 ms	20 ms	10 ms	
		5.36 mJ	4.28 mJ	1.34 mJ	
	Dorsal hand (AP)	100 mA	400 mA	50 mA	400 mA
		20 ms	60 ms	20 ms	400 ms
		2.68 mJ	129 mJ	0.670 mJ	857 mJ

Supplementary Table 2

Mechanical bistability evaluation in clinical samples of healthy individuals (Subject 4, female, age 20; Subject 5, female, age 20; Subject 6, female, 24). Measurements were performed in three skin locations. The absolute value of current and pulse duration required to transition the armature between indented and closed states was measured for $n = 6$ participants. The indentation depth was adjusted by performing experiments with harnesses of varying heights. The skin was preconditioned by indenting it for 30 s before each transition.

		2 mm indentation		1.5 mm indentation	
		Rel. → Com.	Com. → Rel.	Rel. → Com.	Com. → Rel.
Subject 4	Forearm	150 mA	400 mA	100 mA	400 mA
		10 ms	200 ms	10 ms	200 ms
		3.01 mJ	428 mJ	1.34 mJ	428 mJ
	Dorsal hand (MIII)	100 mA	350 mA	50 mA	400 mA
		20 ms	40 ms	10 ms	900 ms
		2.68 mJ	65.6 mJ	0.335 mJ	1930 mJ
	Dorsal hand (AP)	100 mA	400 mA	50 mA	400 mA
		40 ms	100 ms	20 ms	300 ms
		5.36 mJ	214 mJ	0.670 mJ	643 mJ
Subject 5	Forearm	200 mA	400 mA	100 mA	400 mA
		20 ms	40 ms	10 ms	200 ms
		10.7 mJ	85.7 mJ	1.34 mJ	428 mJ
	Dorsal hand (MIII)	200 mA	400 mA	100 mA	400 mA
		10 ms	40 ms	10 ms	200 ms
		5.36 mJ	85.7 mJ	1.34 mJ	428 mJ
	Dorsal hand (AP)	100 mA	400 mA	100 mA	400 mA
		20 ms	40 ms	10 ms	300 ms
		2.68 mJ	85.7 mJ	1.34 mJ	643 mJ
Subject 6	Forearm	100 mA	400 mA	50 mA	400 mA
		20 ms	200 ms	10 ms	200 ms
		2.68 mJ	428 mJ	0.335 mJ	428 mJ
	Dorsal hand (MIII)	250 mA	300 mA	50 mA	400 mA
		10 ms	10 ms	10 ms	100 ms
		8.37 mJ	12.1 mJ	0.335 mJ	214 mJ
	Dorsal hand (AP)	100 mA	400 mA	100 mA	400 mA
		20 ms	20 ms	10 ms	200 ms
		2.68 mJ	42.8 mJ	1.34 mJ	428 mJ

Supplementary Table 3

Performance comparisons between wearable indentation actuator arrays.

Ref.	Tethered	Mechanism	Size*	Blocking holding force (N)	Max extension (mm)	Transition energy (mJ)	Continuous power (mW)
This work	No	Bioelastic/ Electro- magnetic	H 7 mm × D 7 mm (305 mm ³)	1.4 0.6	3	58	NA
This work (scaled)	No	Bioelastic/ Electro- magnetic	H 2.1 mm × D 8 mm (106 mm ³)	0.55 0.3	2	NR	NA
4,5	Yes—high- voltage (2 kV) instrument	Electrostatic	H 0.8 mm × D 10 mm (63 mm ³)	0.75 NA	0.5	NA	200
6	Yes—high- current (3.6 A) instrument	Electro- magnetic	H 13 mm × L 9.5 mm × W 8 mm (1000 mm ³)	NR 0.2	2	180	NA
7	No	Pneumatic	H 18 mm × L 18 mm × W 32 mm (10,300 mm ³)**	0.6 NA	NR	NA	2000
8	Yes— pneumatic pump in backpack	Pneumatic	H 0.14 mm × D 8 mm (7 mm ³)	2.5 NA	2	NA	NR

*Based on dimensions without adhesive layers or supporting electronics.

**Size of pneumatic pump.

NA, not applicable. NR, not reported.

Supplementary Table 4

Performance comparisons between wearable vibration actuator arrays.

Ref.	Tethered	Mechanism	Size ^a	Max frequency tested (Hz)	Continuous power (mW)	Indentation	Bimodal
This work	No	Bioelastic/ Electro-magnetic	H 7 mm × D 7 mm (305 mm ³)	200	134	Yes	Yes
4,5	Yes—high-voltage (2 kV) instrument	Electrostatic	H 0.8 mm × D 10 mm (63 mm ³)	200	200	Yes	No
7	No	Pneumatic	H 18 mm × L 18 mm × W 32 mm (10,300 mm ³) ^b	160	2000	Yes	No
9	No	Electro-magnetic (voice coil)	H 2.4 mm × D 18 mm (610 mm ³)	300	15	No	No
10,11	No	Electro-magnetic (voice coil)	H 1.45 mm × D 5 mm (28 mm ³)	750	14	No	No
12	No	Electro-magnetic (voice coil)	H 4.2 mm × L 12 mm × W 12 mm (605 mm ³)	300	115	No	No
13	No	Electro-magnetic (eccentric rotating mass)	H 2 mm × D 7 mm (77 mm ³)	130 ^c	158	No	No
14	No	Electro-magnetic (eccentric rotating mass)	H 2.7 mm × D 8 mm (136 mm ³)	130 ^c	180	No	No

^aBased on dimensions without adhesive layers or supporting electronics.^bSize of pneumatic pump.^cFrequency is not independently controlled from amplitude.

NA, not applicable. NR, not reported.

Supplementary Table 5

Individual participant responses as part of the vibrotactile perception experiments for relaxed-state vibration (Subject 1, male, age 36; Subject 2, male, age 30; Subject 3, male, age 23; Subject 4, female, age 20; Subject 5, female, age 20; Subject 6, female, age 24; Subject 7, male, age 23; Subject 8, male, age 25; Subject 9, female, age 25; Subject 10, female, age 29; Subject 11, male, age 24; Subject 12, female, age 31). The p-value shows the t-test given the null hypothesis that the mean is zero.

f (Hz)	$I_{\text{coil-pk}}$ (mA)	S1 (%)	S2 (%)	S3 (%)	S4 (%)	S5 (%)	S6 (%)	S7 (%)	S8 (%)	S9 (%)	S10 (%)	S11 (%)	S12 (%)	p-value
50	25	10	10	US*	0	0	0	0	0	0	0	0	US	0.168
	50	30	10	US	0	0	10	0	0	30	0	0	US	0.0697
	100	100	50	US	100	10	40	30	20	70	80	60	US	0.00034
	150	110	90	US	US	120	100	120	50	70	100	80	US	<0.0001
	200	140	120	US	US	160	100	130	80	100	100	80	US	<0.0001
	250	140	150	US	US	180	130	150	140	100	120	US	US	<0.0001
100	25	10	10	0	50	0	0	0	0	0	0	0	0	0.189
	50	50	10	90	110	0	40	10	30	20	0	0	30	0.00919
	100	110	10	110	130	30	80	20	80	90	90	110	80	<0.0001
	150	120	50	110	US	100	120	90	100	100	100	120	US	<0.0001
	200	140	100	US	US	170	140	150	140	100	100	130	US	<0.0001
	250	170	150	US	US	180	150	160	150	120	120	130	US	<0.0001
150	25	10	10	0	10	0	0	0	0	0	0	0	0	0.0819
	50	30	10	70	70	50	40	0	60	30	0	0	10	0.00232
	100	70	50	90	100	70	60	30	80	60	50	80	60	<0.0001
	150	90	110	100	110	80	90	100	90	90	100	110	100	<0.0001
	200	100	120	110	130	100	80	100	90	100	110	100	US	<0.0001
	250	130	150	120	120	110	100	120	110	110	110	100	US	<0.0001
200	25	10	10	0	0	10	0	0	0	0	0	0	0	0.0819
	50	10	10	20	0	30	10	0	50	10	0	10	0	0.014
	100	10	10	30	80	40	20	20	70	30	10	90	30	0.000865
	150	20	30	70	100	80	30	30	80	40	30	90	60	<0.0001
	200	40	100	90	90	60	40	30	80	40	100	80	60	<0.0001
	250	70	110	100	110	90	70	50	80	70	130	100	90	<0.0001

*US, mechanical system was unstable or monostable under the given conditions.

Supplementary Table 6

Individual participant responses as part of the vibrotactile perception experiments for compressed-state vibration (Subject 1, male, age 36; Subject 2, male, age 30; Subject 3, male, age 23; Subject 4, female, age 20; Subject 5, female, age 20; Subject 6, female, age 24; Subject 7, male, age 23; Subject 8, male, age 25; Subject 9, female, age 25; Subject 10, female, age 29; Subject 11, male, age 24; Subject 12, female, age 31) . The p-value shows the t-test given the null hypothesis that the mean is zero.

f (Hz)	$I_{\text{coil-pk}}$ (mA)	S1 (%)	S2 (%)	S3 (%)	S4 (%)	S5 (%)	S6 (%)	S7 (%)	S8 (%)	S9 (%)	S10 (%)	S11 (%)	S12 (%)	p-value
50	25	NR*	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	—
	50	0	0	0	0	0	0	0	0	0	0	0	0	—
	100	0	0	10	0	0	0	0	20	10	10	0	0	0.0538
	150	0	0	40	0	0	0	10	30	20	10	0	0	0.0418
	200	10	10	30	10	0	0	20	70	20	20	0	0	0.018
	250	20	20	40	20	10	20	50	110	30	30	0	0	0.00553
100	25	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	—
	50	0	0	0	0	0	0	0	10	0	0	0	0	0.339
	100	0	0	10	0	0	0	0	80	0	10	0	0	0.234
	150	0	10	30	0	0	0	0	80	20	10	0	10	0.0708
	200	10	10	50	0	10	10	10	90	60	30	0	10	0.0126
	250	20	10	60	10	10	20	10	100	70	100	0	10	0.00743
150	25	0	0	0	0	0	0	0	0	0	0	0	0	—
	50	0	0	30	0	0	0	0	60	0	0	0	0	0.191
	100	0	0	50	0	0	0	0	90	0	10	0	10	0.128
	150	10	10	90	0	0	10	0	90	10	10	0	10	0.0598
	200	10	10	80	30	0	20	10	100	30	50	0	10	0.00918
	250	20	20	80	30	10	30	10	100	80	50	10	10	0.00198
200	25	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	NR	—
	50	0	0	0	0	0	0	0	20	0	0	0	0	0.339
	100	0	0	30	0	0	0	0	80	0	10	0	0	0.173
	150	0	0	60	0	0	0	0	70	0	10	0	10	0.11
	200	0	0	60	0	0	10	10	90	10	20	10	10	0.0439
	250	10	10	80	0	10	20	20	80	20	30	20	10	0.0061

*NR, not recorded.

Supplementary Table 7

Perceived intensities (as defined in Methods) for a ring–disk configuration where the ring is rotated at three possible angles and indented by 0.2 mm (Subject 1, male, age 27; Subject 2, male, age 29; Subject 3, male, age 29; Subject 4, male, age 29; Subject 5, male, age 27; Subject 6, female, age 29; Subject 7, male, age 24; Subject 8, male, age 23; Subject 9, male, age 31; Subject 10, female, age 23; Subject 11, female, age 27; Subject 12, female, age 23; Subject 13, female, age 27; Subject 14, female, age 25).

Rotation and indentation of ring																
Trial	Rotation angle (°)	Indentation (mm)	Subjects													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.33	0.2	1	5	1	1	1	1	1	1	1	1	2	1	2	1
2	0.66	0.2	2	6	2	1	2	2	2	2	2	2	6	2	3	5
3	1	0.2	2	5	2	2	2	3	4	4	4	2	6	2	3	3
4	0.66	0.2	1	4	3	1	2	1	3	3	4	2	6	2	4	2
5	1	0.2	1	5	2	1	3	4	5	5	5	2	6	2	4	5
6	0.33	0.2	1	4	1	1	1	1	1	1	1	1	5	1	1	1
7	1	0.2	3	4	1	1	2	5	3	3	5	2	4	2	3	4
8	0.33	0.2	1	3	1	1	1	2	1	1	1	1	3	1	2	1
9	0.66	0.2	2	4	2	1	2	3	5	5	6	3	4	1	2	3
10	0.33	0.2	1	2	1	1	1	2	2	1	1	1	5	1	1	2
11	0.66	0.2	2	3	1	1	3	5	4	3	5	1	5	2	3	5
12	1	0.2	3	6	2	2	2	4	6	4	7	2	6	2	4	5
13	0.66	0.2	3	4	2	2	1	5	4	2	5	2	5	2	2	4
14	1	0.2	2	4	2	1	2	7	5	3	7	2	5	1	4	3
15	0.33	0.2	1	3	1	1	1	2	2	1	1	1	3	1	1	1

Supplementary Table 8

Perceived intensities (as defined in Methods) for a ring–disk configuration where the disk is rotated at three possible angles and indented by 0 mm (Subject 1, male, age 27; Subject 2, male, age 29; Subject 3, male, age 29; Subject 4, male, age 29; Subject 5, male, age 27; Subject 6, female, age 29; Subject 7, male, age 24; Subject 8, male, age 23; Subject 9, male, age 31; Subject 10, female, age 23; Subject 11, female, age 27; Subject 12, female, age 23; Subject 13, female, age 27; Subject 14, female, age 25).

Trial	Rotation angle (°)	Indentation (mm)	Rotation of disk													
			Subjects													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	5	0	3	1	2	4	4	6	3	3	5	5	5	3	4	4
2	10	0	6	3	4	6	5	6	5	5	6	5	7	4	5	6
3	15	0	7	6	5	7	5	7	4	6	4	6	6	5	6	7
4	10	0	4	4	1	4	5	4	4	3	3	3	5	5	4	5
5	15	0	6	4	5	6	4	6	5	4	3	1	6	4	5	6
6	5	0	1	1	2	3	6	3	2	2	2	3	3	2	2	2
7	15	0	5	4	4	7	3	6	3	4	6	1	4	3	4	6
8	5	0	2	1	2	3	5	5	4	2	3	2	2	1	1	2
9	10	0	4	3	3	4	3	5	5	3	3	1	2	2	3	3
10	5	0	1	1	2	2	4	5	1	1	2	1	1	2	2	1
11	10	0	3	4	3	4	6	4	3	4	4	5	2	3	2	4
12	15	0	6	6	4	7	6	6	4	5	6	2	2	6	6	6
13	10	0	3	3	2	4	4	5	2	4	3	3	1	5	5	3
14	15	0	5	6	4	7	6	7	5	5	6	3	3	5	5	7
15	5	0	1	3	1	3	3	2	2	1	2	1	1	3	1	2

Supplementary Table 9

Perceived intensities (as defined in Methods) for a ring–disk configuration where the disk is rotated at three possible angles and indented by -0.4 mm (Subject 1, male, age 27; Subject 2, male, age 29; Subject 3, male, age 29; Subject 4, male, age 29; Subject 5, male, age 27; Subject 6, female, age 29; Subject 7, male, age 24; Subject 8, male, age 23; Subject 9, male, age 31; Subject 10, female, age 23; Subject 11, female, age 27; Subject 12, female, age 23; Subject 13, female, age 27; Subject 14, female, age 25).

Rotation and indentation of disk																
Trial	Rotation angle (°)	Indentation (mm)	Subjects													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	5	-0.4	3	3	2	7	2	4	2	2	1	2	7	5	2	2
2	10	-0.4	7	6	4	7	4	5	4	4	3	2	7	6	6	3
3	15	-0.4	7	4	4	7	5	7	6	6	5	4	7	7	7	6
4	10	-0.4	6	4	3	7	3	5	5	3	3	2	6	5	3	4
5	15	-0.4	7	4	4	6	4	7	7	5	6	6	7	5	5	6
6	5	-0.4	3	2	5	4	2	2	5	2	2	1	5	4	1	1
7	15	-0.4	6	4	5	7	6	6	7	4	5	4	6	4	4	7
8	5	-0.4	2	2	1	3	3	3	3	1	1	2	4	3	2	1
9	10	-0.4	5	1	3	6	3	6	5	3	4	3	4	3	3	4
10	5	-0.4	2	1	2	4	2	4	1	1	2	1	4	2	1	1
11	10	-0.4	5	3	3	6	3	5	2	3	3	3	4	2	3	3
12	15	-0.4	7	4	5	7	5	7	4	4	4	4	5	4	3	6
13	10	-0.4	2	3	4	5	4	7	3	2	2	1	3	3	6	2
14	15	-0.4	5	4	6	6	6	6	6	3	3	3	6	4	7	5
15	5	-0.4	1	1	1	3	1	3	5	1	1	1	4	1	1	1

Supplementary Table 10

Perceived intensities (as defined in Methods) for a ring–disk configuration where the ring and disk are rotated at three possible angles and indented by 0.2 mm and –0.4 mm respectively (Subject 1, male, age 27; Subject 2, male, age 29; Subject 3, male, age 29; Subject 4, male, age 29; Subject 5, male, age 27; Subject 6, female, age 29; Subject 7, male, age 24; Subject 8, male, age 23; Subject 9, male, age 31; Subject 10, female, age 23; Subject 11, female, age 27; Subject 12, female, age 23; Subject 13, female, age 27; Subject 14, female, age 25).

Rotation and indentation of ring and disk																
Trial	Rotation angle (°)	Indentation (mm)	Subjects													
			1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	0.33 & 5	0.2 & –0.4	3	3	3	6	6	7	7	3	2	3	3	2	2	2
2	0.66 & 10	0.2 & –0.4	4	5	4	6	7	7	7	4	7	5	4	5	3	2
3	1 & 15	0.2 & –0.4	5	5	5	7	6	5	6	6	7	5	6	5	7	4
4	0.66 & 10	0.2 & –0.4	4	4	4	7	6	4	5	2	6	2	4	4	2	5
5	1 & 15	0.2 & –0.4	6	5	5	7	7	5	6	3	5	2	6	5	3	7
6	0.33 & 5	0.2 & –0.4	2	3	3	4	5	4	3	1	3	1	3	3	1	3
7	1 & 15	0.2 & –0.4	5	5	4	7	6	5	4	4	3	3	4	4	5	7
8	0.33 & 5	0.2 & –0.4	3	2	2	4	5	4	1	1	2	2	2	3	3	2
9	0.66 & 10	0.2 & –0.4	2	5	3	6	5	4	4	2	5	3	4	4	2	5
10	0.33 & 5	0.2 & –0.4	2	4	2	3	4	4	3	1	2	2	3	4	1	2
11	0.66 & 10	0.2 & –0.4	5	5	4	5	4	7	2	2	5	3	3	5	5	6
12	1 & 15	0.2 & –0.4	6	6	5	7	5	7	5	3	5	4	5	6	4	7
13	0.66 & 10	0.2 & –0.4	5	4	4	3	5	5	3	3	4	4	4	6	2	6
14	1 & 15	0.2 & –0.4	5	5	5	6	6	7	5	6	3	5	6	7	6	7
15	0.33 & 5	0.2 & –0.4	2	4	3	3	4	4	2	1	2	1	1	4	3	4

Supplementary Table 11

Extended statistical analysis of the torsion perception experiments using the Friedman Test and Dunn Test.

Rotation and indentation of the ring	Friedman Test			Dunn Test (Bonferroni Correction)		
	chi-squared	df	p-value	Compared rotation angles	z-value	p-value
	25.48	2	<0.0001	0.33° – 0.66°	–3.34	0.0026
				0.33° – 1°	–4.07	0.00014
				0.66° – 1°	–0.74	1.000
Rotation of the disk	Friedman Test			Dunn Test (Bonferroni Correction)		
	chi-squared	df	p-value	Compared rotation angles	z-value	p-value
	26.14	2	<0.0001	10° – 15°	–2.49	0.0380
				10° – 5°	2.56	0.0312
				15° – 5°	5.06	<0.0001
Rotation and indentation of the disk	Friedman Test			Dunn Test (Bonferroni Correction)		
	chi-squared	df	p-value	Compared rotation angles	z-value	p-value
	27.53	2	<0.0001	10° – 15°	–2.43	0.0452
				10° – 5°	2.48	0.0398
				15° – 5°	4.91	<0.0001
Rotation and indentation of the ring and disk	Friedman Test			Dunn Test (Bonferroni Correction)		
	chi-squared	df	p-value	Compared rotation angles	z-value	p-value
	26.14	2	<0.0001	(0.33°, 5°) – (0.66°, 10°)	–2.74	0.0182
				(0.33°, 5°) – (1°, 15°)	–4.68	<0.0001
				(0.66°, 10°) – (1°, 15°)	–1.93	0.1600

Supplementary Table 12

Statistical analysis of the torsion perception experiments using paired t-test.

Rotation of the disk vs. Rotation & indentation of the disk	Paired t-test (H0: true difference in means is equal to 0)					
	Rotation Angle	Indentation	t-value	df	95% confidence interval	p-value
	5°	0 vs. -0.4 mm	0.257	13	[-0.636, 0.807]	0.802
	10°	0 vs. -0.4 mm	-0.325	13	[-0.656, 0.485]	0.751
Rotation & indentation of the ring & disk vs. Rotation & indentation of the disk	Paired t-test (H0: true difference in means is equal to 0)					
	Rotation Angle	Indentation	t-value	df	95% confidence interval	p-value
	(0.33°-5°) vs. 5°	-0.4 mm	1.616	13	[-0.168, 1.168]	0.130
	(0.66°-10°) vs. 10°	-0.4 mm	1.186	13	[-0.317, 1.088]	0.257
Rotation & indentation of the disk	(1°-15°) vs. 15°	-0.4 mm	-0.323	13	[-0.440, 0.326]	0.752

Supplementary Table 13

Results of the Spearman's rank correlation (ρ) coefficient analysis for torsion perception experiments.

Subject	Rotation & indentation of ring		Rotation of disk		Rotation & indentation of disk		Rotation & indentation of ring & disk	
	ρ	p-value	ρ	p-value	ρ	p-value	ρ	p-value
1	0.653	0.0083	0.880	<0.0001	0.789	0.0005	0.847	<0.0001
2	0.532	0.0414	0.907	<0.0001	0.738	0.0017	0.846	<0.0001
3	0.592	0.0202	0.818	0.000193	0.712	0.0029	0.913	<0.0001
4	0.408	0.1309	0.927	<0.0001	0.592	0.0200	0.761	0.00098
5	0.765	0.0009	0.208	0.458	0.916	<0.0001	0.522	0.0458
6	0.712	0.0029	0.398	0.142	0.871	<0.0001	0.492	0.0622
7	0.828	0.0001	0.633	0.0114	0.669	0.0064	0.468	0.0785
8	0.874	0.00002	0.784	0.0005	0.691	0.0043	0.772	0.00075
9	0.828	0.0001	0.523	0.0457	0.822	0.0002	0.606	0.0167
10	0.847	0.00007	0.308	0.263	0.790	0.0005	0.600	0.0181
11	0.580	0.0235	0.712	0.0029	0.350	0.2005	0.912	<0.0001
12	0.745	0.0014	0.825	0.0002	0.385	0.1570	0.748	0.00133
13	0.829	0.0001	0.299	0.279	0.818	0.0002	0.575	0.0249
14	0.735	0.0018	0.683	0.0050	0.880	<0.0001	0.720	0.00249
Overall	0.580	<0.0001	0.596	<0.0001	0.649	<0.0001	0.599	<0.0001

Supplementary Table 14

Number of accurate discriminations between indentation and torsion, individual results for 15 healthy participants (10 repeated measures; Subject 1, female, age 26; Subject 2, female, age 27; Subject 3, female, age 27; Subject 4, female, age 25; Subject 5, male, age 31; Subject 6, male, age 27; Subject 7, male, age 29; Subject 8, male, age 29; Subject 9, female, age 23; Subject 10, male, age 26; Subject 11, female, age 23; Subject 12, male, age 29; Subject 13, male, age 24; Subject 14, female, age 25; Subject 15, female, age 29).

Unit	Subjects														
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
A	10	10	10	10	10	7	10	10	10	10	10	10	10	10	10
B	9	8	10	9	10	10	10	10	10	10	10	10	9	10	10
C	10	10	10	10	10	10	10	10	10	10	10	8	10	10	10
D	10	10	9	10	10	9	10	10	10	10	9	9	10	9	10

Supplementary Table 15

Number of accurate discriminations between patterns of torsion, individual results for 12 healthy participants (10 repeated measures; Subject 1, female, age 27; Subject 2, male, age 31; Subject 3, male, age 27; Subject 4, male, age 29; Subject 5, male, age 29; Subject 6, female, age 23; Subject 7, male, age 26; Subject 8, female, age 23; Subject 9, male, age 29; Subject 10, male, age 24; Subject 11, female, age 25; Subject 12, female, age 29).

Pattern	Subjects											
	1	2	3	4	5	6	7	8	9	10	11	12
P1	6	7	8	10	9	5	4	10	5	6	7	7
P2	8	7	9	9	10	6	7	10	4	10	8	10
P3	6	7	10	9	10	10	9	9	8	10	10	9
P4	5	9	5	9	9	8	8	10	8	8	9	10

Supplementary Table 16

Participant balance durations as part of the Sharpened Romberg task (Subject 1, female, age 35; Subject 2, female, age 35; Subject 3, female, age 20; Subject 4, female, age 29; Subject 5, female, age 32; Subject 6, male, age 36; Subject 7, male, age 20; Subject 8, male, age 34; Subject 9, male, age 33; Subject 10, male, age 24).

		S1 (s)	S2 (s)	S3 (s)	S4 (s)	S5 (s)	S6 (s)	S7 (s)	S8 (s)	S9 (s)	S10 (s)
Rep. 1	A*	15.68	10.88	64.6	43.73	9.49	13.9	35.37	40.73	14.67	46.86
	B*	8.09	28.43	39.39	71.15	102.67	36.36	21.97	18.44	27.82	43.81
	B	305.47	8.78	200.06	74.94	74.79	30.9	13.91	49.02	30.71	22.47
	A	17.72	10.61	68.38	8.63	67.49	26.72	3.22	18.14	1.62	9.46
	<i>Relative** change</i>	<i>838.8%</i>	<i>73.2%</i>	<i>80.1%</i>	<i>179.0%</i>	<i>130.5%</i>	<i>65.6%</i>	<i>-7.0%</i>	<i>14.6%</i>	<i>259.3%</i>	<i>17.7%</i>
Rep. 2	B	121.34	27.16	53.05	34.64	317.94	32.5	63.44	85.92	25.44	17.51
	A	57.75	15.09	220.21	37.57	23.64	30.5	9.21	44.26	11.36	7.93
	A	120.03	9.85	60.86	38.57	103.5	7.78	18.43	13.14	30.38	20.21
	B	147.21	21.77	12.55	72.44	51.35	42.33	36.56	86.94	40.86	28.73
	<i>Relative change</i>	<i>51.1%</i>	<i>96.2%</i>	<i>-76.7%</i>	<i>40.6%</i>	<i>190.5%</i>	<i>95.5%</i>	<i>261.8%</i>	<i>201.1%</i>	<i>58.8%</i>	<i>64.3%</i>
Rep. 3	A	57.63	17.67	49.04	32.45	180.93	32.15	5.54	24	83.75	20.83
	B	454.59	22.5	141.72	33.28	99.14	44.66	16.42	44.99	26.96	10.08
	B	309.53	34.52	35.17	67.02	120.48	33.61	7.1	10.94	15.87	13.12
	A	78.34	20.33	62.48	20.03	110.13	36	23.97	48.48	7.96	11.21
	<i>Relative change</i>	<i>462%</i>	<i>50.1%</i>	<i>58.6%</i>	<i>91.1%</i>	<i>-24.5%</i>	<i>14.8%</i>	<i>-20.3%</i>	<i>-22.8%</i>	<i>-53.3%</i>	<i>-27.6%</i>
Rep. 4	B	12.1	79.13	27.1	44.36	65.12	15.67	11.33	60.77	11.15	12.1
	A	10.71	88.09	23.64	49.16	6.5	18.53	31.81	14.79	36.25	10.71
	A	18.38	54.44	24.55	18.18	19.39	14.62	49.3	10.81	20.23	18.38
	B	39.42	315.82	89.95	122.09	21.44	6.61	51.32	31.56	35.58	39.42
	<i>Relative change</i>	<i>136.6%</i>	<i>77.1%</i>	<i>177.1%</i>	<i>142.9%</i>	<i>147.2%</i>	<i>234.3%</i>	<i>-32.8%</i>	<i>-22.8%</i>	<i>260.7%</i>	<i>-17.3%</i>
Rep. 5	A	8.41	126.96	52.27	77.12	17.6	24.36	32.48	19.53	17.24	8.41
	B	36.58	229.1	72.79	49.2	17.17	4.5	87	35.34	54.76	36.58
	B	36.12	38.16	122.42	260.39	63.15	13.22	40.9	54.37	8.71	36.12
	A	9.18	40.86	39.7	155.61	12.97	6.02	20.17	19.83	21.31	9.18
	<i>Relative change</i>	<i>77.7%</i>	<i>313.3%</i>	<i>59.3%</i>	<i>112.3%</i>	<i>33%</i>	<i>162.7%</i>	<i>-41.7%</i>	<i>142.9%</i>	<i>127.9%</i>	<i>64.6%</i>

*A indicates an attempt without feedback, and B indicates an attempt with feedback.

**Relative change in balance duration with feedback relative to balance duration without feedback. The quantity was calculated from the mean values from the two conditions in each repetition.

Supplementary Table 17

Participant error measured during the foot strike task with feedback. In Phases 1–3, Subject 1 (male, age 37) had step intervals 2.10 ± 1.04 s, 1.68 ± 0.481 s, and 1.07 ± 0.257 s respectively. In Phases 1–3, Subject 2 (female, age 35) had step intervals 1.72 ± 0.274 s, 1.44 ± 0.226 s, and 0.901 ± 0.127 s respectively. In Phases 1–3, Subject 3 (male, age 21) had step intervals 1.65 ± 0.459 s, 1.38 ± 0.321 s, and 0.964 ± 0.276 s respectively.

Subject	Orientation (ψ, φ)	Phase	Trial 1 (°)	Trial 2 (°)	Trial 3 (°)	Trial 4 (°)	Trial 5 (°)	Mean (°)	Mean $\pm$ SD (°)
1	(15°, -60°)	1	5.50	5.01	7.03	6.45	—	5.99	8.09 $\pm$ 3.95
		2	2.54	3.79	7.58	8.91	—	5.71	
		3	13.39	10.68	9.07	17.11	—	12.56	
	(0°, 0°)	1	3.70	16.14	3.94	2.72	0.87	5.47	4.59 $\pm$ 4.15
		2	5.05	4.79	5.94	7.65	0.93	4.87	
		3	0.93	1.18	0.69	10.88	3.40	3.42	
	(30°, 0°)	1	13.33	9.84	14.59	5.04	14.44	11.45	11.21 $\pm$ 4.04
		2	14.10	15.07	16.73	10.79	14.66	14.27	
		3	9.50	4.37	11.45	3.28	11.01	7.92	
	(15°, 60°)	1	10.60	13.40	9.51	11.96	10.38	11.17	10.19 $\pm$ 3.90
		2	6.09	10.25	19.69	14.92	11.59	12.51	
		3	5.83	7.51	5.57	11.13	4.37	6.88	
2	(15°, -60°)	1	11.58	14.01	13.68	7.28	—	11.64	12.02 $\pm$ 4.50
		2	8.03	6.76	8.79	9.67	—	8.31	
		3	15.64	17.83	8.75	21.93	16.45	16.12	
	(0°, 0°)	1	13.27	1.09	7.76	2.74	15.63	8.10	8.07 $\pm$ 4.73
		2	16.06	9.62	12.49	7.18	3.86	9.84	
		3	5.77	10.69	2.48	3.06	9.40	6.28	
	(30°, 0°)	1	15.17	10.49	15.08	4.50	—	11.31	12.14 $\pm$ 6.24
		2	11.96	17.44	2.14	20.58	—	13.03	
		3	4.47	16.37	6.39	21.04	—	12.07	
	(15°, 60°)	1	13.79	6.40	11.45	3.29	6.07	8.20	7.37 $\pm$ 3.70
		2	4.56	15.73	6.05	7.27	2.19	7.16	
		3	6.79	8.33	9.51	4.69	4.45	6.75	
3	(15°, -60°)	1	12.95	4.89	5.20	3.95	6.30	6.66	8.84 $\pm$ 5.61
		2	10.65	6.58	6.21	16.21	16.33	11.20	
		3	4.40	1.95	14.81	2.16	19.95	8.65	
	(0°, 0°)	1	2.89	14.05	14.43	8.54	2.09	8.40	5.39 $\pm$ 5.87
		2	3.08	1.33	3.11	1.31	3.77	2.52	
		3	20.33	1.03	1.16	0.68	3.10	5.26	
	(30°, 0°)	1	4.74	1.28	12.54	11.07	11.82	8.29	8.32 $\pm$ 5.06
		2	13.81	5.75	10.18	13.36	5.49	9.72	
		3	18.91	2.22	2.03	3.78	7.90	6.97	
	(15°, 60°)	1	9.02	17.35	3.97	3.38	7.98	8.34	10.23 $\pm$ 5.10
		2	11.42	5.11	13.42	12.83	18.66	12.29	
		3	17.90	10.07	13.07	5.40	3.84	10.06	

Supplementary Table 18

Participant error measured during the foot strike task without feedback (control; Subject 1, male, age 37; Subject 2, female, age 35; Subject 3, male, age 21).

Subject	Orientation (ψ, ϕ)	Trial 1 (°)	Trial 2 (°)	Trial 3 (°)	Trial 4 (°)	Trial 5 (°)	Mean $\pm$ SD (°)
1	(15°, -60°)	11.30	10.73	10.12	14.81	18.23	13.04 $\pm$ 3.07
	(0°, 0°)	16.47	6.68	9.46	8.99	11.42	10.60 $\pm$ 3.30
	(30°, 0°)	17.61	11.74	17.00	25.16	43.01	22.91 $\pm$ 10.93
	(15°, 60°)	11.99	13.49	21.92	23.30	10.09	16.16 $\pm$ 5.39
2	(15°, -60°)	8.60	20.76	14.02	12.51	16.88	14.55 $\pm$ 4.10
	(0°, 0°)	7.80	15.10	12.83	16.63	16.65	13.80 $\pm$ 3.31
	(30°, 0°)	6.20	4.07	34.15	15.98	11.54	14.39 $\pm$ 10.72
	(15°, 60°)	13.15	5.70	3.55	7.17	3.21	6.56 $\pm$ 3.60
3	(15°, -60°)	7.07	14.59	5.55	9.97	15.66	10.57 $\pm$ 4.00
	(0°, 0°)	2.25	3.51	1.11	2.46	2.21	2.31 $\pm$ 0.76
	(30°, 0°)	17.06	18.97	17.60	27.26	28.86	21.95 $\pm$ 5.05
	(15°, 60°)	9.73	9.63	7.79	15.46	13.22	11.17 $\pm$ 2.77

Supplementary Video 1

Animated diagram (left) and three-dimensional digital image correlation (DIC; 0.004× playback speed) results (right) illustrating operation of the bistable structure (F_{skin} , the reactive force of skin; F_{hold} , the holding force from the permanent magnet; F_{contact} , the force of contact between the armature and opposing surfaces; F_{coil} , the force applied by driving the coil with current).

Supplementary Video 2

Three-dimensional digital image correlation (DIC) measurements of vibrotactile stimuli ($I_{\text{coil-pk}} = 250$ mA, $f = 50$ Hz; 500 Hz sample rate; 0.05× playback speed) on a skin phantom (45:1 PDMS, $E = 43$ kPa). (left) Relaxed-state vibration. (middle) Compressed-state vibration. (right) Full-transition vibration ($I_{\text{coil-pk}} = 300$ mA).

Supplementary Video 3

Two-tiered, counter-rotating kirigami transducer operating on human skin (forearm). A current amplitude of $I_{\text{coil}} = 500$ mA was applied for transitions to and from the compressed state.

Supplementary Video 4

Three-dimensional digital image correlation (DIC) measurements of the kirigami transducer delivering shear force ($I_{\text{coil}} = 500$ mA) on a skin phantom (50:1 PDMS, $E = 31$ kPa).

Supplementary Video 5

Temperature colormap of the haptic array, imaged from the adhesive, skin-facing surface using an infrared camera (a6255sc, FLIR Systems). During imaging, the array was driven with conditions matching continuous operation during the visual sensory substitution task (7 transitions/s over the entire array, max 0.7 transitions/s on individual transducers, 100 mJ per transition). The video was recorded over 15 minutes (3× playback speed).

Supplementary Video 6

Annotated demonstration of the haptic transducer array as sensory substitution for visual impairment.

Supplementary Video 7

Example demonstration of navigation strategies utilized by one blindfolded participant (male) traversing an obstacle course with feedback from the visual sensory substitution system. The participant wore a LiDAR-enabled smartphone around their neck to continuously map their physical surroundings. Aside from the haptic device, rendering smartphone-derived sensory information as patterns of indentation on the back of their neck, no other feedback was given to the participant. The participant was given no prior information on the path configured in this video prior to recording.

Supplementary Video 8

Example demonstration of navigation strategies utilized by one blindfolded participant (female) locating a chair with feedback from the visual sensory substitution system. The participant wore a LiDAR-enabled smartphone around their neck to map and classify their physical surroundings. Colored surfaces on the smartphone indicate object classification (blue, chairs; purple, desks; gray, doors). The haptic array included a torsional unit which informed the user when they were facing a chair. The participant was given no prior information on the location of the chair prior to recording, and they were given no other feedback besides torsion and indentation from the haptic array.

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