Flexible soft tactile sensors enable the robotic arms to gain real-time mechanical responses, which are of utmost importance for future deep learning in robotic sciences and technologies. Learning from nature will inspire the advances of soft tactile sensors as mother nature is proficient in achieving unique functionality at the simplest construction. Herein, the fabrication of self-powered soft tactile sensors is reported. The shape of flexible sensors mimics Merkel’s disks, allowing for a well tactile perceptual functionality. Due to the use of flexible magnetoelectric materials, the sensors are self-powered without external power supply. This unique functionality is explained by Maxwell’s numerical simulation, allowing for further improvement of their performance by adjusting diverse fabrication factors. Furthermore, such self-powered soft tactile sensors are attached to the tips of a robotic arm, enabling the arm to distinguish different objects after smart learning. The soft sensor design reported here is expected to manifest in a range of self-powered sensing systems, opening up as yet unexplored avenues for the development and the exploitation of future intelligent robots and their deep learning.

1. Introduction

Flexible soft tactile sensors were born in the past two decades yet exhibit their potential to bring forth the next revolution in replacement prosthetics and human–computer interaction, especially for robotic arms. Different from rigid counterparts, soft tactile sensors can easily attach to curved, even irregular, surfaces of objects, enabling the robotic arms to gain real-time mechanical responses for their further judgment. In addition, making the robotic arms to feel more sensitive, very recently, soft tactile sensor arrays upon a glove realized a deep learning of human grasps to distinguish different objects. This interesting study can guide the development of humanoid robotic arms to identify and then deal with different stuff. Therefore, considerable attention has been paid by diverse groups in this field. In spite of multitudinous efforts devoted in the sensor fabrication, two issues are crucial for enabling such electronics. The former one is the design of sensors. Although pyramid arrays or sea urchin-shaped sensors have exhibited ultrahigh sensitivity to detect tiny vibrations, the general rules for the shape design of sensors are not clear. The latter one is the power supply of flexible sensors. Most currently reported flexible sensors rely on commercial batteries, which not only occupy limited space for constructing sensing devices but also bring in considerable running costs, as well as potential pollution to the environment.

To solve the two issues mentioned earlier in sensor fabrication, learning from nature will be a promising strategy as nature continuously inspires the advances of human science and technology. The organs of human beings have been developing for millions of years of evolution, allowing them to adapt and then communicate with the surroundings. As the largest organ of the human body, the skin can modulate the body...
temperature, as well as sense external stimuli for informing the brain.\cite{28} To sense diverse applied forces from the environment, the skin develops four kinds of receptors embedded inside its surfaces, of which Merkel’s disks are particularly important due to their pressure-sensitive features to tune slowly adapting type-I (SA-I) mechanoreceptor nerve fibers.\cite{29,30} The shape of Merkel’s disks is an inverted cone (Figure 1a,b), allowing for new understandings to build artificial tactile sensors after carefully studying such natural teachers. In addition, the nano-channels connected with the Merkel’s disks can respond to external mechanical force and then generate electrical signals through the Na⁺/K⁺ ionic pump.\cite{31} This biological teacher can inspire a self-powered concept, by converting external forces to the electrical power, which not only minimizes the space of sensing organs but also provides unlimited power to run the device under the externally mechanical stimuli. Thus, it is believed that mimicking Merkel’s disks can guide the design of new and self-powered soft tactile sensors and boost the advances of flexible sensors and related fields.\cite{32,33}

Herein, we demonstrate the fabrication of bioinspired self-powered soft tactile sensors based on flexible magnetoelectric materials (Figure 1c). The shape of flexible sensors mimics Merkel’s disks, allowing for well tactile perceptual functionality. The mechanism for such a shape design toward optimized sensing performances has been studied. Due to the use of flexible magnetoelectric materials, the sensors are self-powered and can convert mechanical stimuli to electrical signals. This unique functionality has been explained by Maxwell’s numerical simulation, allowing for further improvement of their performance by adjusting magnetic powder filling content, sensor shapes, and magnetic fields.

Figure 1. Merkel’s disks bioinspired magnetoelectric tactile sensors. Schematic illustrations of a) one type of sensing unit—Merkel’s disks in the skin of a human finger, b) one Merkel’s disk unit, and c) a tactile sensor composed of a top magnetic elastomer and bottom electrical part. The magnetic flux pass along the Z-axis of top frustum-shaped Nd₂Fe₁₄B magnetic powders/Ecoflex composite toward bottom coiled copper rings. When being compressed by an external force, the frustum-shaped magnetic mixture will deform, inducing the change in such a magnetic flux and the generation of electric signals. d) Schematic illustration of an in situ high-resolution X-ray micro-CT technique to obtain a reconstructed 3D copy of the magnetic composite for its inside detailed information. e) Optical image of as-prepared magnetoelectric tactile sensors. f) A reconstructed 3D copy, g) 2D (y–z plane), and h) (x–y plane) micro-CT images of frustum-shaped Nd₂Fe₁₄B magnetic powders/Ecoflex composite.
compression rate, and other factors. Furthermore, such self-powered soft tactile sensors have been attached to the tips of a robotic arm, enabling the arm to distinguish different objects after smart learning. We believe that this kind of bioinspired design is a powerful strategy to fabricate self-powered flexible sensors toward the smart learning of next-generation robotics.

2. Results and Discussion

Figure 1e shows a photograph of the as-prepared soft tactile sensor, entitled HUST-3. The device is composed of two parts: the top magnetic part to mimic Merkel’s disks and bottom electrical one. Generally, Nd$_2$Fe$_{14}$B magnetic powders, with a diameter ranging from 100 to 200 $\mu$m (Figure S1, Supporting Information), were uniformly dispersed in Ecoflex liquid with a weight ratio of 7/3, yielding a dark and viscous mixture. Such a liquid mixture was carefully poured into a 3D-printed mold with an inverse shape of Merkel’s disk (Figure S2, Supporting Information). The liquid mixture became a frustum-shaped elastomer (with a top diameter of 8 mm and bottom diameter of 2 mm) after being heated at 50 °C for 30 min and easy to demould. To obtain a uniformly oriented magnetic field in the elastomer, a magnetizing post-treatment was conducted, treating its bottom side (smaller area) as the north pole. As a result, parallel magnetic lines could pass along the Z-axis of the frustum-shaped mixture (Figure 1c). In the following procedure, coiled copper wires were embedded in a thin layer of Ecoflex and placed under the Nd$_2$Fe$_{14}$B powders/Ecoflex frustum-shaped elastomer, constructing a flexible magnetoelectric sensor. Unless otherwise specified, the copper wires were coiled into seven concentric rings and kept at a 1 mm Ecoflex gap from the bottom surface of the magnetic part.

We used a high-resolution X-ray microcomputed tomography (micro-CT) technique to investigate the dispersion of magnetic powders inside the mixture (Figure 1d). Micro-CT is an in situ, nondestructive 3D imaging system to gain structural information of solid composites. Figure 1f–h shows the 3D reconstructed, 2D ($y$–$z$ plane), and 2D ($x$–$y$ plane) images of a magnetic frustum-shaped mixture, respectively. It clearly shows that Nd$_2$Fe$_{14}$B powders were uniformly dispersed in the Ecoflex elastomer. Bright and dark regions represent the magnetic powders and silicone elastomer, respectively. As the Nd$_2$Fe$_{14}$B magnetic powders were embedded in the elastic Ecoflex, the whole composite can be compressed and recover quickly (Figure S3, Supporting Information). An obvious hysteresis loop presents in the compression-recovery curves, indicating that the magnetic frustum-shaped mixture has a viscoelastic mechanical characteristic.

As shown in Figure 1c, a magnetic flux passes along the Z-axis of the frustum-shaped magnetic mixture toward the bottom coiled copper concentric rings. When being compressed by an external force, the frustum-shaped magnetic mixture will deform, allowing the change of such a magnetic flux. According to Faraday’s law of induction,$^{134}$ the changing magnetic flux through the electrical circuit will generate electrodynamic potential, detected as voltage output signals. To prove this hypothesis, we conducted a mechanical–electrical test with the as-fabricated sensor on a home-made testing system (Figure S4, Supporting Information). Regular electrical outputs can be found when applying an interval loading/unloading compression strain, which can be analogized as piezoelectric ability (Figure 2a). The average voltage value (dark blue plots) reaches around 20 $\mu$V at a compressing ratio of 30% with the compressing speed set at 800 mm min$^{-1}$. The shapes of downward (Figure 2b) and upward (Figure 2c) electrical pulses show a double-peak feature for each cycle of compressing the elastomer. For comparison, a control experiment using a pure Ecoflex elastomer without any Nd$_2$Fe$_{14}$B powder filling was performed. Unfortunately, no electrical response exists, indicating the importance of the magnetic/electrical synergetic effect of the soft tactile sensor. It should be noted that the whole device was self-powered without any external power supply.

In addition to the qualitative analysis in Figure 2b,c, a quantitative numerical simulation via Ansys Maxwell software was performed to explain the working mechanism of this piezoelectric capacity. Previous studies$^{[35,36]}$ are only able to calculate the distribution of magnetic intensity around a few magnetic bulks. For treating the complex magnetic powder matrix, existing approaches cannot obtain their magnetic intensity distribution due to limited computer capacities. Therefore, an equivalent model, by treating binary magnetic powders/polymer as a unary magnet (Figure 2d), has been used in Maxwell’s numerical simulation in this study to simplify the calculation (the details of equivalent models can be found in Note S1 and Figure S3, Supporting Information). The distribution of the magnetic density of these two models along the Z-axis is shown in Figure 2e. The curve of the binary magnetic powder matrix in the polymer (blue line) is in coincidence with that of an equivalent unary model (red line). These results show that binary magnetic powders/polymer (weight ratio of 7/3) can be simplified as a unary magnet, by decreasing the residual magnetism Br to 0.3 times of that of the bulky Nd$_2$Fe$_{14}$B (0.7875 T) in the same shape, in the Ansys Maxwell finite element analysis.

Then, a frustum-shaped magnetic elastomer before/after a 30% compression strain was visualized, monitored by a high-speed camera system (Figure 2f,g). The deformation of the frustum-shaped elastomer caused by an external force mainly induced a change in the bottom area due to its asymmetric shape design with a wide top yet a narrow bottom. Figure 2h,i shows the finite element mechanical simulation results of the frustum-shaped magnetic elastomer before/after a 30% compression strain, which was conducted with the energy-based nonlinear elastic constitutive model (the details of simulations can be found in Note S2, Supporting Information). The color bar in Figure 2j, from blue to red, represents the gradually increased deformation energy. It is obvious that the deformation energy mostly focused on the bottom region of the frustum-shaped magnetic elastomer.

Based on the visual observation and mechanical analysis, the magnetic flux of the frustum-shaped magnetic elastomer before/after compression can be calculated. The binary magnetic powders/polymer system can be simplified as a unary magnetic system (Figure 2k,l). The simulation modeling used a 2D static magnetic field solver with horizontal X-axis and vertical Z-axis. The unary magnetic system was set as a frustum, 8 mm (top diameter) × 2 mm (bottom diameter) × 4 mm (height), followed by magnetizing in the direction of the positive Z-axis according to Nd$_2$Fe$_{14}$B parameters. The color bar in Figure 2m, from blue
to red, represents the gradually increased magnetic intensity. It clearly shows that the strongest magnetic intensity appears on the bottom and top edges of the unary magnetic system. The bottom copper concentric wires were equivalent to the same number of concentric rings for a simplified calculation. As a result, the total magnetic flux of the frustum-shaped magnetic elastomer before/after compression can be calculated using the following Equation (1)\[34\]

$$E(V) = -N \cdot \Delta \Phi / \Delta t = - \sum_{i=1}^{i} \Delta \Phi_i / \Delta t = - \sum_{i=1}^{i} \left( \Phi_i \text{(after)} - \Phi_i \text{(before)} \right) / \Delta t$$ (1)

where $E(V)$ is output voltage, $N$ is the number of concentric rings of the coiled copper wire, $\Delta \Phi$ is total magnetic flux change, $\Delta \Phi_i$ is magnetic flux change of each equivalent ring, and $\Delta t$ is the response time of the elastomer.
A gap distance of 1 mm was fixed between the elastomer bottom and the copper concentric rings. When a compression strain is applied, the unary frustum-shaped system will deform, inducing an increased magnetic flux passing through the bottom copper rings (Figure 2k). In this case, an electric voltage output was generated (Figure 2b). The total magnetic flux changes through the copper rings before/after compression can be calculated according to Equation (1). Taking the 30% strain as an example, the total magnetic flux through the copper rings before and after the applied pressure is $6.57 \times 10^{-6}$ Wb and $9.08 \times 10^{-6}$ Wb (see Note S3, Supporting Information, and Table 1), respectively. As a result, the change of magnetic flux is $2.51 \times 10^{-6}$ Wb.

Furthermore, the number of copper rings also affected the output voltage (Figure 3d). By tuning the circle number from one to seven circles, the voltage outputs were increased from 3.1 to 18.6 $\mu$V, which fits with the theoretically calculated results (Note S4 and Table S3, Supporting Information). The gap between the elastomer bottom and the copper rings shows a downside effect on the output voltage (Figure 3e). As shown in Figure S9 and Table S4, Supporting Information, a larger gap could decrease the magnetic flux change through the copper rings, yielding a reduced voltage output. The compression speed has a significant influence on the electrical response and the results in Figure S10, Supporting Information, showed that the faster it compressed, the higher the voltage output obtained. The compression strain rate was fixed at 5%. After optimizing the parameters of soft tactile sensors, we investigated their long-life stability. The result is shown in Figure S11, Supporting Information. The sensor exhibits a stable response to the interval for up to 10,000 cycles. By applying a series dynamic pressure, we test the pressure detection limit of the frustum-shaped magnetic elastomers, and the results in Figure S12, Supporting Information show that it can respond to a dynamic pressure as low as 0.9 kPa. In the comparison with other capacitive-type\(^{[17]}\) or magnetic MEMS-type\(^{[38]}\) pressure sensors (Table S5, Supporting Information), our magnetic elastomer tactile sensor still has rather poor performance in terms of the pressure detection limit, response time, and volume size. The highlight of our work is the self-powering characteristic of this magnetic elastomer tactile sensor. We believe the performance can be improved by additional structure and parameter optimization, such as inducing the gap air as demonstrated in the work.

In the aforementioned paragraphs, we investigated the self-powered feature of as-prepared magnetoelectric soft sensors. However, the general rules for the shape design of such sensing organs require deep understanding. Thus, we fabricated three kinds of inverted frustum-shaped (Figure S13–S15, Supporting Information), as well as a hemisphere-shaped, magnetic elastomers (Figure S16, Supporting Information and Figure 4) to compare their piezoelectric capacities. All magnetic elastomers exhibited a similar top diameter of 8 mm, yet different bottom diameters from 8 mm (cylinder) to 6 or 4 mm (inverted frustum), then to nearly 0 mm (hemisphere). To distinguish different samples, we nominated these samples by the ratio ($R$) of top diameter/bottom diameter.

As-prepared elastomers with diverse $R$ values deformed differently under the same compression. Loading an external force of 3.2 N (equal to 0.064 MPa), the cylinder-shaped ($R = 1$) elastomer exhibited a strain of only 13.1%. In contrast, the inverted frustum-shaped counterparts showed strain values of 14.6% ($R = 1.3$), 20.5% ($R = 2$), and 30% ($R = 4$), respectively. It shows that the decrease in the bottom diameter of the elastomers can lead to an increased strain, indicating the wisdom of biological teachers to design the shape of their sensing organs. These results can be explained by the energy-based nonlinear elastic constitutive models, as shown in Figure 4a–h. Similar to the symmetric shape of the cylinder in Figure 4a, the compression strain applied to the elastomer was uniformly absorbed and spread out along the entire block (Figure 4e). Alternatively, because of the asymmetric shapes of inverted frustums and hemisphere

### Table 1. Calculated total magnetic flux of the frustum-shaped sensor before/after a compression with a pressure loading at 3.2 N (0.064 MPa).

| Total magnetic flux before compression [$\times 10^{-6}$ Wb] | Total magnetic flux after compression [$\times 10^{-6}$ Wb] | The change of magnetic flux [$\times 10^{-6}$ Wb]|  
|-----------------|-----------------|-----------------|---|
| $6.57$          | $9.08$          | $2.51$          |   

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Figure 3. Diverse parameters affect the electrical output of magnetoelectric tactile sensors. The open-circuit output voltage of magnetoelectric tactile sensors fabricated with different a) Nd$_2$Fe$_{14}$B powder weight contents, b) compression strain rates, c) thickness of frustum-shaped magnetic elastomers, d) the number of copper concentric rings, and e) distance between the frustum-shaped magnetic elastomers and copper concentric rings. Unless otherwise specified, other parameters remained the same, whereas only one was adjusted to study its influence on the electrical performance of the magnetoelectric elastomer. The compressing speed in all the aforementioned experiments was set at 800 mm min$^{-1}$ at room temperature.
Figure 4b–d), the narrow bottom regions bore most deformation energy, allowing for larger deformations (Figure 4f–h).

As shown in Figure 3b, a larger strain indicated increased magnetic flux change, as well as voltage outputs. Thus, we calculated the magnetic intensity distributions of those elastomers with diverse shapes based on the Ansys Maxwell finite element analysis (Figure 4j–q). As we expected, asymmetric shapes enabled the elastomers to gain a larger deformation. Table 2 shows the calculated magnetic flux change for each sample under the same pressure loading of 3.2 N (equal to 0.064 MPa). It is
obvious that a smaller bottom diameter can generate a larger change of magnetic flux, especially for the hemisphere-shaped sample. Figure 4s–v shows the voltage outputs of those four samples. This trend is in accordance with the theoretically calculated trend. Notably, the hemisphere-shaped sample exhibited a maximum voltage output of 24.1 μV under the same pressure, showing its potential in further practical application.

Tactile perceptual functioning and smart learning are the trends of the next-generation robot developments.19,46 Due to the advanced piezoelectric capacity of the hemisphere-shaped sample (Figure 4t), the self-powered sensor was carefully attached to one tip of a robotic arm (Figure 5a–c), allowing the robotic arm to feel and then respond to diverse objects. Five stuffs with diverse material species and Young’s moduli, including a soft rubber ball (an Ecoflex shell filled with viscose fluid, see Figure 5d), a solid Ecoflex cube (Figure 5e), a light and porous sponge cube (Figure 5f), a paperboard cube (four square layers taped together, see Figure 5g), and a metallic battery (Figure 5h), were selected as the study objects of the robotic arm.

Each object was gripped and then released by the robotic arm several times to study their feature signals (Figure S17, Supporting Information). Due to diverse Young’s moduli of these five kinds of stuffs, the deformation of the magnetoelectric sensor was different, leading to diverse voltage outputs (Figure 5i–m). Because gripping/releasing objects with diverse Young’s moduli caused different deformations of the sensor, the value of output $V_{\text{grip}}$ and $V_{\text{release}}$ and their ratio ($V_{\text{grip}}/V_{\text{release}}$) can be regarded as the characteristic peaks to distinguish the objects. During the studying process, each object underwent at least 20 picking-up/releasing cycles to ensure the stability of studied electrical data.

After studying the feature signals of diverse objects, a blind picking test was performed to verify the studying effect. The robotic arm with the self-powered sensor was placed in an impenetrable box (Figure 5n). By programming the instruction, the robotic arm picked up and then released an unknown volunteer object (Movie S1, Supporting Information and Figure 5o). The regular output voltage signal was collected by the voltmeter aside, showing a $V_{\text{grip}}$ of $-10\, \mu\text{V}$ and a $V_{\text{C}}/V_{\text{P}}$ ratio valued at $-2.3$. These characteristic peaks are close to that of the light and porous sponge cube (Figure 5k), enabling the robot to judge the object as the sponge cube. Finally, the impenetrable box was lifted (Figure 5k), showing the evidence that is in accordance with the judgment of the robotic arm. This demonstration shows the potential of our self-powered magnetoelectric sensor to help smart learning of robotic arms.

3. Conclusions

This work demonstrates a bioinspired self-powered tactile sensor by mimicking the shape and perceptual functionality of Merkel’s disks. The mechanism for such a shape design toward optimized sensing performances has been achieved using a magnetoelectric elastomer comprising magnetic powders and polymers. Both experimental and Maxwell’s numerical simulation results confirmed that the magnetic flux change induced by the mechanical stimuli generates electrical voltage output, and the whole process is self-powered. Furthermore, by varying the shape of the magnetic elastomer, an originated yet beyond biological structure was developed, showing optimized performance. The integration of this magnetoelectric elastomer sensor to a robotic arm can help the robot distinguish different types of subjects. The structure design of this self-powered sensor would make a significance for future intelligent robot and machine learning.41,42

4. Experimental Section

Fabrication of Bioinspired Magnetoelectric Elastomers: A photocuring 3D printer (ANYCUBIC Photon) was used to assist the fabrication of magnetoelectric elastomers. Nd$_2$Fe$_{14}$B powders (100 mesh, Guangzhou Xinnuode Transmission Parts Co., Ltd.) with an average diameter of 150 μm were mixed with commercial two-component liquid silicone (Ecoflex, T605#A&B) in different weight ratios (10:90, 20:80, 30:70, 40:60, 50:50, 60:40, 70:30, and 80:20). The mixture was solidified in a 3D-printed mold (see Figure S1, Supporting Information) with a hollow frustum shape at 50 °C for 30 min. The frustum had a top of 8 mm in diameter and a bottom of 2 mm in diameter. The solidified mixture then underwent a magnetizing treatment at 1600 V on a magnetizer (MA-2030, Shenzhen Juju Industrial Equipment Co., Ltd.). In control experiments, the samples of the magnetic elastomers were adjusted by varying the diameter of bottom regions from 4 to 6 mm and 8 mm. A hemisphere with a diameter of 8 mm was also fabricated. Commercial copper wires with thicknesses of 0.2 mm in diameter were coiled into concentric circles (14 mm diameter of the outer circle) and then were sealed with commercial two-component liquid silicone (Ecoflex, T605#A&B). The gap between the magnetic elastomer and the encapsulated copper concentric rings was adjusted by adding an Ecoflex sheet with 1–3 mm thicknesses. Unless otherwise specified, coiled seven-circle encapsulated copper concentric rings were used with the outer diameter of 14 mm and inner diameter of 2 mm.

Characterization: The optically digital images of elastomers were recorded using a commercial digital camera (α6300, Sony). The morphological image of Nd$_2$Fe$_{14}$B powders was captured with an optical microscope (MF43, Mshot). Nd$_2$Fe$_{14}$B particles were also characterized with environmental scanning electron microscopy (ESEM, Quanta 200, FEI, Holland) at an accelerating voltage of 20 kV. The magnetic intensity on the surface of the as-prepared magnetic elastomers was measured by WT10A Teslamer (WEITE Magnetic Technology Co., Ltd., China). The electrical responses of the samples to the cyclic loading–unloading compression were recorded by a data acquisition and multimeter system (DMM 6500, Tektronix) with an internal impedance of 1 MΩ. A compressive test apparatus (HDE-S-500, Haibao Instrument Co., Ltd., China) was used to modulate the compressive parameters for cyclic pressure tests. To record the real-time compressing status of the magnetic sensors, a MEMRECAM HX-7s high-speed camera system (ST-857, NAC Image

| Sample         | Compression rate [%] | Total magnetic flux before compression [$\times 10^{-5}$ Wb] | Total magnetic flux after compression [$\times 10^{-5}$ Wb] | The change of magnetic flux [$\times 10^{-5}$ Wb] |
|----------------|----------------------|-------------------------------------------------------------|----------------------------------------------------------|------------------------------------------------|
| Cylinder       | 13                   | 13.53                                                       | 14.15                                                   | 0.62                                          |
| Frustum-6      | 14.5                 | 11.11                                                       | 11.89                                                   | 0.78                                          |
| Frustum-4      | 20                   | 8.97                                                        | 10.21                                                   | 1.24                                          |
| Hemisphere     | 18.3                 | 8.27                                                        | 11.77                                                   | 3.50                                          |

Table 2. Calculated total magnetic flux of diverse samples with different shapes before/after a compression with a pressure loading at 3.2 N (0.064 MPa).
Figure 5. Robotic arm’s tactile perceptual functioning and smart learning based on magnetoelectric tactile sensors. a) Optical image of a commercial robotic arm. b) is a magnified image of (a), showing that the self-powered sensor is carefully attached to one tip of the robotic arm. Due to its advanced piezoelectric capacity of magnetoelectric tactile sensors, the robotic arm can feel and then to respond to diverse objects. c) is a schematic illustration of (b). Optical images of five objects, including d) a soft rubber ball (Ecoflex shell filled with viscose fluid), e) a solid Ecoflex cube, f) a light and porous sponge cube, g) a paperboard cube (four square layers taped together), and h) a metallic battery, are selected for the robotic arm studying process. i–m) are the open-circuit output voltages of the magnetoelectric tactile sensors by gripping and then releasing (d–h), respectively. Because gripping/releasing objects with diverse Young’s moduli caused different deformations of the sensor, the values of output $V_{\text{grip}}$ and $V_{\text{release}}$ and their ratio ($V_{\text{grip}}/V_{\text{release}}$) can be regarded as the characteristic peaks to distinguish the objects. n) Schematic illustration of testing the studying effect of the sensor loading robotic arm. Optical images of (o) show a blind experiment by allowing the robotic arm to pick up and then release an unknown volunteer object. The whole process was performed in a black box. Based on the regular output voltage signals, the robot can judge the object as the sponge cube. p) The impenetrable box was lifted, showing evidence that is in accordance with the judgment of the robotic arm.
Technology Inc.) controlled by MEMRECAM HXLINK (SP-642) was used in this study. The mechanical tests of the samples were conducted on All-ElectroPuls Electric Dynamic Test Instrument (E1000, Instron). The high-resolution X-ray microcomputed tomography (micro-CT) characterization of the magnetic samples was conducted on a D X-ray microscope (Xradia 510 Versa, Carl Zeiss).

Numerical Simulation: Abaqus 6.13-1 was used to conduct the finite element analysis simulation based on the nonlinear elastic constitutive model. The deformation energy model was used to analyze the strain distribution inside the magnetic elastomer.

The Ansys Maxwell finite element analysis software was used to conduct 2D modelings of the magnetic elastomer placed upon copper rings with the same centers and varied diameters (14 mm, 12, 10, 8, 6, and 2 mm). The magnetizing process was performed in the direction of the positive Z-axis (the top for S and the bottom for N pole) according to NdFeB parameters. The copper concentric rings involved in experiments were equivalent to rings with the same centers and varied diameters (14 mm, 12, 10, 8, 6, 4, and 2 mm).

Supporting Information
Supporting Information is available from the Wiley Online Library or from the author.

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Conflict of Interest
The authors declare no conflict of interest.

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