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Research on the Application of Flexible Tactile Sensors in Braille Recognition

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Abstract. Braille is an important tactile writing system for visually impaired people, but its small dot height (about 0.35 mm) sets very high demands on sensitivity and spatial resolution in tactile sensors. Flexible tactile sensors can fit snugly on fingertips and record t static pressure and dynamic sliding as well. They have advantages over rigid sensors. This paper reviews flexible tactile sensing schemes for Braille recognition, focusing on piezoresistive, capacitive, iontronic, and triboelectric mechanisms. It also covers microstructure design and crosstalk suppression. Now, reported devices already have sensitivities up to 0.43 nF kPa−1, and have limits as low as 33 Pa, and have recognition rates between 91.25% and 98.96% for Braille letters. Neuromorphic and machine-learning-assisted systems maintain a word-level accuracy over 90% at different scanning speeds and indentation depths. Optical fiber and tactile and auditory systems have reached 98.57% dot-arrangement classification and completely accurate word and sentence classification. Gradient modulus isolation layer has reached a sensitivity of 3.92 kPa−1, 4.39% crosstalk, 100% static Braille recognition, and 99% dynamic recognition accuracy. However, most of these data are under ideal conditions, but still face challenges in reality. Future work should combine strain-insensitive architectures, low-crosstalk arrays, and robust algorithms to develop practical Braille-reading products for visually impaired users. By summarizing the progress and limitations of existing studies, this review aims to provide insights into material selection, structural design, and system integration for practical Braille-reading devices for visually impaired users.

Keywords: Flexible tactile sensor, Braille recognition, Crosstalk suppression, Microstructure, Machine learning

1. Introduction

Braille reading is a basic skill for visually impaired people, and it places high demands on the tactile sensing system for the fingertips. Standard Braille dots are small and very close to each other, so the sensor must distinguish clear spatial features in sliding contact and remain comfortable. Traditional rigid sensors are difficult to conform to the curved fingertips and often fail to capture small moving signals in Braille reading. Compared to this, flexible sensors can simulate the mechanical properties of human skin [1]. They can be classified into piezoresistive, capacitive, piezoelectric, and triboelectric types according to their force-electric conversion mechanisms [1, 2]. Although there has

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been rapid progress, most of the flexible sensors that are used for Braille recognition are still being tested under ideal laboratory conditions, and practical challenges such as uneven pressure, surface deformation, and environmental disturbance remain insufficiently addressed. So, it is necessary to systematic review of different sensing mechanisms and clarify future directions.

Flexible tactile sensors are widely used in Braille recognition because they can conform to fingertips and capture both static pressure and dynamic sliding. Recent research converts flexible pressure sensors into piezoresitive, capacitive, piezoelectric, and triboelectric types [1, 2]. Piezoresistive sensors are easy to read out but have a delay; capacitive sensors provide stable static response but are susceptible to parasitic capacitance crosstalk in high-density arrays [1]. Iontronic sensing exploits electric double layers at ionic liquid-electrode interfaces and can achieve ultrahigh interfacial capacitance; an iontronic microdroplet array reached 0.43nF kPa^{-1} sensitivity and a 33 Pa detection limit [3]. Machine-learning frictional electric sensor has a recognition accuracy of up to about 99.58% for six types of dynamic touch modalities [4]. For Braille recognition, a micro-dome piezoresostove sensor with dimensions matched to Braille dot achieved 98.96% of recognition for 26 letters [5]; E-skin based on binary memristive neural network reached to 91.25% accuracy and lower the cost for hardware [6]; Neuromorphic BrailleNet has a word level accuracy which is bigger than 90% under different scaning speed and indentation depths [7]; tactile-to-auditory system reached 97% letter ang 96% digit recognition [8]; An optical fiber ring resonator using PHD demodulation achieved 98.57% dot arrangement classification and completely accurate word and sentence classification [9]. In order to suppress crosstalk, a gradient high/low modulus strain isolation layer enabled 3.92 kPa^{-1} sensitivity, 4.39%crosstalk, 100%static and 99% dynamic Braille recognition [10]. Biomimetic fiber-entangled e-skin achieved 100 unit cm^{-2} pixel density and a gauge factor lower than 0.03 and 96.77% Braille classification [11]. Microstructures such as micro-domes amplify local deformation and improve spatial resolution.

Although progress has been made, most of the demonstration are still rely on standardized Braille templates, stable humidity and temperature, and fixed pressing force. In reality, the conditions are more complex than laboratory settings, and practical devices for blind users are still limited. So this paper reviews the mainstream flexible tactile sensing schemes for Braille recognition. It aims to clarify the theoretical principles, materials, microstructures, and crosstalk suppression methods, and analyzes their advantages , limitations, and practical applicability. The remainder of this paper is organized as follows: Section 2 introduces the sensing mechanisms and material systems. Section 3 talks about case studies on microstructure design, array resolution and crosstalk suppression; Section 4 compares key parameters and discusses real-world applications; Section 5 is the conclusion of the whole paper.

Braille remains one of the most important channels through which blind and visually impaired people access information, yet learning and reading Braille still pose significant challenges. Traditional Braille materials are often bulky, expensive, and difficult to revise, while rigid tactile sensors struggle to conform to the curved fingertip and capture subtle dynamic contact. Flexible tactile sensors offer a promising alternative because they are soft, lightweight, and capable of detecting both static pressure and dynamic sliding. Over the past decade, various sensing mechanisms and microstructures have been explored for Braille recognition, and many prototypes have achieved encouraging accuracy under laboratory conditions. However, there is still a gap between laboratory demonstrations and practical devices that can be used comfortably and independently in daily life. This review aims to bridge this gap by systematically comparing existing approaches and identifying future directions.

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2. Methodology

This paper uses the methods of literature research and comparative induction; it does not include original experiments but instead summarizes and compares existing studies on flexible tactile sensors for Braille recognition instead. The methodology consists of four parts: sensing mechanism models, signal processing and machine learning models, evaluation metrics, and data sources.

2.1. Sensing mechanism models

Flexible tactile sensors convert mechanical stimuli into electrical signals by different mechanisms. Piezoresistive sensors rely on the change in resistance, which could be described by

$$R = \rho L / A \tag{1}$$

where ρ is resistivity, L is length, and A is cross-sectional area [1]. Capacitive sensors detect capacitance change, given by the formula

$$\mathscr{E}_0 \mathscr{E}_r A / d \tag{2}$$

where $\mathscr{E}_0$ is the vacuum permittivity, $\mathscr{E}_r$ is the relative permittivity, A is the overlap area, and d is the separation [1]. Iontronic sensors exploit electric double layers at ionic liquid-electrode interfaces, achieving ultrahigh interfacial capacitance [3]. Triboelectric sensors convert mechanical stimulation into electrical signals through contact electrification and electrostatic induction [4]. Optical fiber sensors detect resonance shifts caused by pressure-induced strain and photoelastic effects [9].

2.2. Signal processing and machine learning models

A lot of different machine learning models have been used to decode tactile signals for Braille recognition. Support vector machine (SVM) classifies dynamic touch modalities [4]. Convolutional neural networks (CNN) that extract spatial features from pressure maps are widely used in Braille character recognition [4, 7]. Residual network (ResNet)-based models improve classification accuracy under different scanning speeds and indentation depths [7]. Long short-term memory (LSTM) network process time-series tactile signals for word and sentence classification [8]. Multilayer perceptrons (MLP) classify dot arrangements [9].

2.3. Evaluation metrics

Key evaluation metrics for Braille recognition include sensitivity, detection limits, crosstalk, spatial resolution, recognition accuracy, response time, and stability. Sensitivity is defined as [1].

$$S = \frac{\Delta C / C_0}{\Delta P} \tag{3}$$

The crosstalk coefficient is defined as [10].

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$$CTK(\%) = 100 \times \frac{\Delta C_{around}}{\Delta C_{center}} \tag{4}$$

Recognition accuracy is equal to $N_{correct}/N_{total}$. Strain interference is often evaluated by the gauge factor [11].

$$GF = \frac{\Delta S/S_0}{\varepsilon} \tag{5}$$

2.4. Data sources

Common data sources in this field include standardize Braille boards, 3D-printed Braille templates, different dot heights, different scanning speeds, and different indentation depths [7, 12, 13]. These datasets are used to train and test recognition models under controlled and variable conditions.

3. Theoretical principles

Flexible tactile sensor has a great potential in assisting Braille reading. Compared to traditional rigid silicon-based sensor, it is softer and can simulate a real human fingertip. Depending on different mechanisms of force-electric conversion, flexible tactile sensors nowadays can be separated into piezoresistive, capacitive, ionic conductive, and triboelectric [1, 2]. Materials determine core indicators of the device, including sensitivity, spatial resolution, and environmental stability; these performance parameters directly depends if the sensor can identify standard Braille dots with a height of approximately 0.35mm or not [5]. For Braille reading scenario, the sensor needs to collect static pressing pressure and dynamic sliding vibration signals. This brings challenges for a single-mechanism sensor.

3.1. Piezoresistive sensors

A piezoresistive sensor converts pressure into a resistance change. When mechanical deformation is happening, the conductive network inside is reconstructed and produces resistance differences that can be measured [1]. This kind of sensor can readout circuit easily, and has a low prize of making it. However, the hysteresis effect is still an unavoidable disadvantage that affects measurements in real situations [1].

3.2. Capacitive sensors

Capacitive sensors work by detecting capacitance changes. Pressure compressed delectric layer between two electrode plates; the capacitance increases as well [1]. Capacitive sensors feature low power consumption and stable static-pressure response. But high-density capacitive array may easily suffer from crosstalk caused by parasitic capacitance interference [1]. Iontronic sensing uses electric double layers at ionic liquid-electronic interfaces; an iontronic microdroplet array achieved 0.43 nF kPa^{-1} sensitivity and a 33 Pa detection limit [3]. The gradient modulus isolation layers can alleviate the crosstalk problem [10].

DOI: 10.54254/2753-8818/2027.MB39131

3.3. Ionic-conductive sensors

The ionic-conductive sensors are mainly made of ionic liquids or ionic gel materials. External pressure changes the contact area at the ionic-electrode interface, which can be measured as a capacitance change [3]. These sensors can be very soft and touch-like skin.

3.4. Triboelectric sensors

Triboelectric nanogenerators convert mechanical stimulation into an electric signal by contact electrification and electrostatic Induction [4]. Machine-learning-assisted triboelectric nanogenerators tactile sensors have a recognition accuracy of up to about 99.58% for the 6 types of dynamic touch modalities [4]. They are suitable for dynamic sliding but not that good for static pressure [1].

4. Case study

4.1. Microstructure design and spatial resolution

Spatial discrimination was really important in distinguishing tiny Braille dot features. Normal flat sensing layers cannot capture the slight height difference of the raised dots in braille, microstucture modification is an effective solution. A micro-dome structure whose dimension matches braille dots can amplify local contact deformation and strengthen weak tactile signals. One micro-dome-based sensor achieved 98.96 % recognition accuracy for 26 English Braille letters under sliding-mode test [5]. As shown in Fig. 1, the micro-dome structure amplifies local contact deformation, and the confusion matrix demonstrates high recognition accuracy across 26 letters.

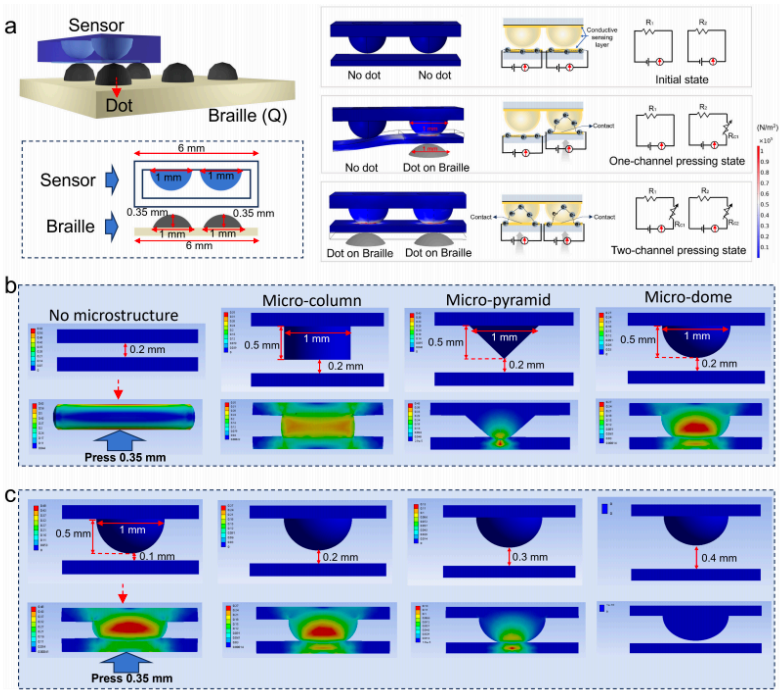


Figure 1. Micro-dome sensor structure and Braille recognition results. Adapted from Ref. [5].

As shown in Fig. 1, the micro-dome structure amplifies local contact deformation. A biomimetic fiber-entangled e-skin achieved 100 unit cm^{-2} pixel density and a gaude factor less than 0.03 [11].

DOI: 10.54254/2753-8818/2027.MB39131

Micro-pyramids and porous structures also amplify local pressure and improve resolution [1] . All in all, the microstructure enhances spatial resolution by amplifying local pressure, thereby solving the problem of identifying micrometric Braille dots.

4.2. Crosstalk suppression

In order to separate the adjacent Braille dots clearly, the tactile sensor requires a high-density sensing pixel array. Mechanical and electrical coupling effects between adjacent units will produce crosstalk and make the Braille dot boundaries not clear. There are two major ways of suppressing crosstalk: structural optimization and algorithm compensation. Structural strategies include gradient modulus strain-isolation layers (SIL); a gradient high/low modulus strain-isolation layer (G-HL-SIL) array achieved 3.92 kPa^{-1} sensitivity and 4.39% crosstalk, enabling 100% static and 99% dynamic Braille recognition [10].

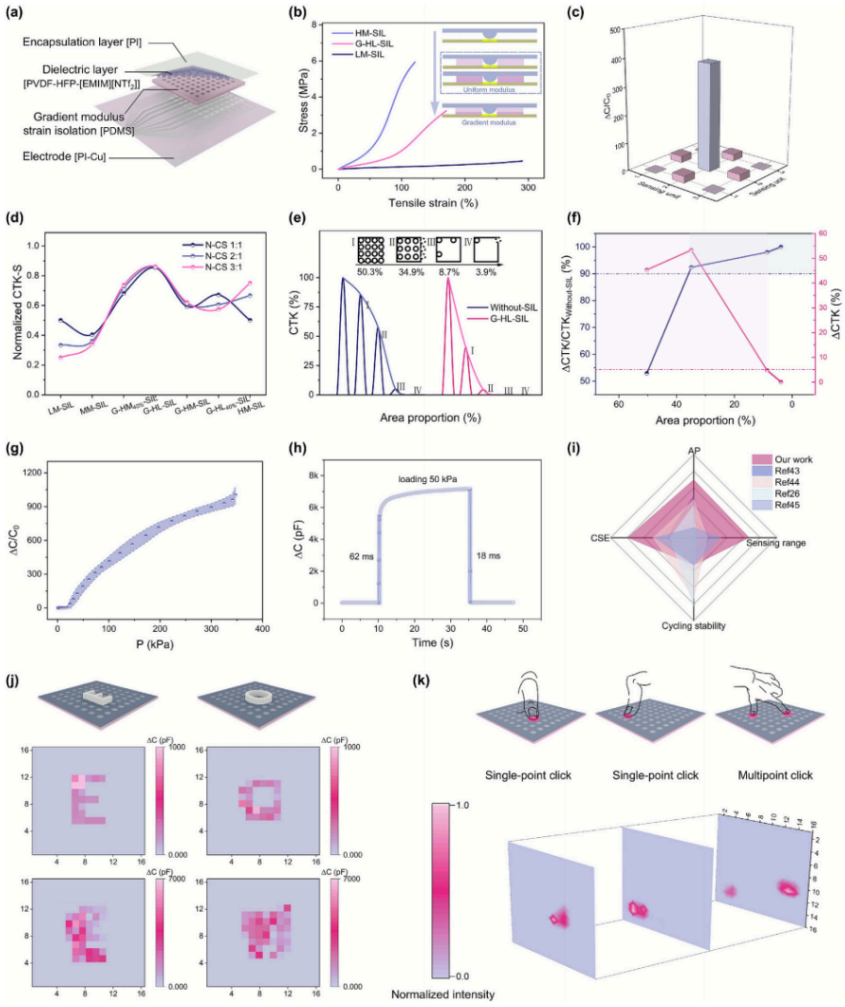


Figure 2. G-HL-SIL array structure, crosstalk suppression performance, and Braille recognition results. Adapted from Ref. [10].

As shown in Fig.2, the gradient modulus isolation layer effectively suppresses crosstalk while maintaining high sensitivity. On the software side, machine learning algorithms such as SVM and

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CNN can deal with sensing data [4]. It should be noted that crosstalk suppression often involves trade-offs with fabrication complexity and other performance metrics.

4.3. Representative Braille recognition prototypes

Currently, a representative prototype device for Braille recognition. has achieved good result in the test in the experiment. The micro dome sensor was small and has a letter recognition accuracy of 98.96% [5]. E-skin based on memristor has a recognition accuracy of 91.25% and decreases handware computing overhead [6]. As shown in Fig. 3, the E-skin system maintains high recognition accuracy even under weight noise. Neuromorphic BrailleNet can maintain over 90% word-level accuracy under varied scanning speed and indentation depth [7]. A tactile-to -auditory system reached 97% letter and 96% digit recognition [8].

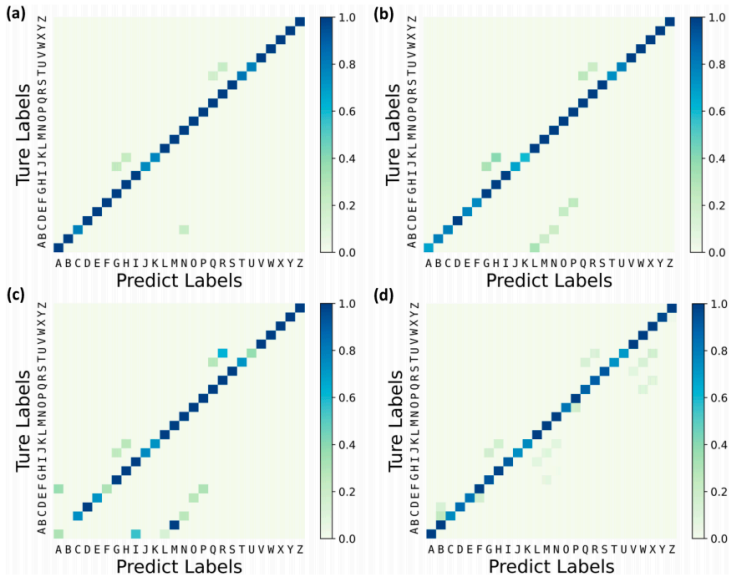


Figure 3. Confusion matrices for 26-alphabet recognition by the E-skin system under different scenarios: (a) without weight noise, (b) with ±10% weight noise, (c) with ±20% weight noise, and (d) measurement result. Adapted from Ref. [6].

However, in reality, disturbances such as uneven finger pressure, paper-Braille surface deformation, humidity changes, and surface dirt can significantly degrade device performance. Up to now, these things are all based on laboratory products, but seldom turn into products that face blind people. Even so, existing research provides valuable references for material selection, structural design, and processing of practical Braille-reading equipment.

5. Analysis and discussion

5.1. Comparison of mainstream sensing mechanisms

From four mainstream mechanisms, piezoresistive, capacitive, triboelectric, and ionic-conductive, they are compared by sensitive, detection limit, crosstalk, static and dynamic response, and Braille recognition accuracy. Piezoresistive sensors are easy to read out and have low cost, but suffer from hysteresis [1]. Capacitive sensors are sensitive and stable in static conditions; iontronic sensors provide high sensitivity and a 33 Pa detection limit [3]. However, high-density capacitive arrays are

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susceptible to parasitic crosstalk [1], which can be mitigated by gradient modulus isolation layers [10]. Triboelectric sensors are suitable for dynamic sliding, with a recognition accuracy of about 99.58% for 6 types of dynamic touch modalities [4], but they are not so good for static pressure [1]. Ionic-conductive sensors are soft and suitable for skin, but the environmental stability still needs to improved.

5.2. Performance metrics for Braille recognition

The key indices for Braille recognition include spatial resolution, sensitivity, crosstalk, and recognition accuracy. A micro-dome piezoresistive sensor has a recognition accuracy of up to 98.96% for 26 English letters [5]. An e-skin based on a binary memristive neural network has reached 91.25% accuracy and reduced hardware cost [6]. Neuromorphic BrailleNet remains a word-level accuracy higher than 90% under different sliding speeds and indentation depths [7]. A tactile-to-auditory system has letter recognition up to 97% and digit recognition up to 96% [8]. An optical fiber ring resonator with PHD demodulation achieved 98.57% dot-arrangement classification and completely accurate word and sentence classification [9]. A gradient modulus isolation layer has 3.92 kPa^{-1} sensitive, 4.39% crosstalk, and 100% static and 99% dynamic Braille recognition [10]. A fiber-entangled e-skin achieved 100 unit cm^{-2} pixel density, a gauge factor less than 0.03, and 96.77% classification [11].

5.3. Real-world challenges

Almost all the experiments that have been mentioned were based on Standard Braille templates, stable temperature and humidity, and fixed pressing force as well. In reality, disturbances such as uneven finger pressure, paper-Braille surface deformation, humidity changes, and surface dirt can significantly decrease device performance. These problems are still not fully solved nowadays, and most of the products are still in the process of experimentation, but not few of them face blind users.

6. Limitations and future outlooks

Although flexible tactile sensors have achieved a high accuracy in Braille recognition, they still have several limitations. First, most of the reported devices are tested under standardized Braille templates, stable temperature and humidity, and fixed pressing force. In real use, uneven finger pressure, paper-Braille surface deformation, humidity changes, and surface dirt can significantly change contact conditions and reduce signal quality. Secondly, high sensitivity and low crosstalk are still in contradiction. Dense arrays are necessary for resolving adjacent Braille dots, but mechanical and electrical coupling between pixels can blur dot boundaries [10, 11]. Structural isolation layers and algorithmic compensation can alleviate this problem, but they often increase fabrication complexity, device thickness, or computational cost. Third, lots of high-performance devices rely on special materials, cleanroom fabrication, or external signal processing , which limits scalability and affordability. Fourth, although machine learning increases the recognition, models are often trained on limited datasets and may not generalize across different users, Braille boards, scanning speed, and indentation depths [4, 7]. Fifth, there are only few researches report long-term wearability, biocompatibility, and user experience for blind users [11]. Despite these limitations, the rapid progress in flexible tactile sensing suggests that Braille-reading devices are moving from proof-of -concept demonstrations toward real-world applications.

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Future work can be proceed in several different directions. First, strain-insensitive and low-crosstalk architectures need to be further developed, for example, fiber-entangled e-skins and gradient modulus isolation layers [10, 11]. Second, multimodal sensing that combines pressure, vibration, and may better mimic human tactile afferents and improve robustness [14]. Third, embed lightweight and explainable machine into wearable or portable hardware for real-time Braille reading [6-8]. Fourth, establish a standardized benchmark, including different Braille materials, dot heights, scanning speeds, and environmental conditions. Last but not least, form a close collaboration with visually impaired users, which is essential to move from laboratory prototypes to practical, affordable, and comfortable Braille reading products [11]. Ultimately, the goal of these efforts is not only to improve sensor performance but also to provide blind and visually impaired users with more convenient, affordable, and independent access to information. Close collaboration with end users will be essential to ensure that future devices truly meet their daily needs.

7. Conclusion

This paper reviewed flexible tactile sensors for Braille recognition from principles to practical cases, Piezoresistive, capacitive, iontronic, piezoelectric, and triboelectric mechanisms each have distinct trade-offs. Capacitive arrays can achieve high sensitivity and low crosstalk, while piezoresistive microstructures provide simple, high accuracy character recognition. Machine-learning and neuromorphic processing improve dynamic decoding, with a word-level accuracy higher than 90% and E-skin recognition at 91.25%. Optical fiber and tactile-to-auditory systems further expanded the design space . However, most of the devices still remain laboratory prototypes under ideal conditions; real-world applications such as humidity, dirt, uneven pressure, and surface deformation still haven't been solved. More follow-up work can be done. Further work should focus on strain-insensitive structures, low-crosstalk iontronic sensor arrays, and robust algorithms. The aim is to make wearable, cheap, and reliable Braille reading products for visually impaired people.

It is hoped that future Braille readers can achieve high accuracy and truly improve the daily lives of blind and visually impaired users. Other than lab data like sensitivity, resolution, and recognition rate, the real value of this technology is simple: can people wear it comfortably, use it alone, and get it at low cost in daily life. So future researchers should talk more with visually impaired users. They need to learn their real reading habits and troubles, and turn technical progress into useful tools for study, communication, and social activities. In the end, these flexible touch sensors for Braille are not only made to create better sensors. They help blind users get fairer information and more independence in their daily lives.

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