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Smart gloves-based triboelectric nanogenerator for sign language detection

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Abstract

Sign language is frequently used to facilitate communication between the normal and individuals having speaking and hearing difficulties. In this work, a triboelectric nanogenerator (TENG) based on smart gloves was designed for a self-powered sign language detection system. The TENG was fabricated using flexible materials like copper, aluminum electrodes, and polyethylene fabric (PE). To accommodate many finger positions and the backside of fingers as separate channels, the TENG was made to be both circular and rectangular in shape. Employing PE fabric as an active layer, these TENG devices can successfully harvest biomechanical energy from finger motions while being comfortable for the fingers. The TENG device with 4 cm × 4 cm dimensions demonstrated the highest voltage and current of 220 V and 750 nA, respectively, whereas the highest power of the device is 65 µW at 500 MΩ resistance. The TENG device was effectively used to charge various capacitors and power a low-power digital watch. The electrical outputs from performing the sign language gestures were collected using the TENG and translated into digital signals using Python. This sign-language detection based on the TENG system is completely tailorable, easy to fabricate, low-cost, and wearable. The emergency sign languages can be easily translated into text signals and can be recognized by non-signers, and take immediate action for the required scenarios.

Keywords Sign-language detection, Python, Signal processing, SOS, Triboelectric

Introduction

Sign language detection in an emergency is crucial for ensuring effective and timely communication between first responders and individuals having speaking and hearing disabilities [1, 2]. In emergencies such as natural disasters, medical crises, or accidents, the inability to communicate essential information can delay rescue efforts, medical attention, or evacuation, potentially leading to life-threatening outcomes [3, 4]. Automated sign language detection systems can bridge this communication gap by instantly translating sign language into text or speech, enabling responders to understand the needs of individuals quickly and accurately [5–8]. This technology ensures that no one is left unheard in critical moments, fostering inclusivity and saving lives through rapid and effective communication [9, 10].

Triboelectric nanogenerators (TENGs) have become a potential device for self-powered wearable electronics due to their ability to transform low-frequency mechanical motions into electrical signals [11, 12]. TENGs are simple devices that can convert mechanical energy into electrical energy with the help of triboelectricity and electrostatic induction [13–15]. This is especially useful for applications like sign language identification, as natural human gestures are very gentle. TENG devices are extremely sensitive to minor mechanical deformations, are mechanically flexible enough to adjust to body

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movements, and can be designed using simple, low-cost methods [16–18]. Furthermore, their compatibility with skin-contact and textile-based platforms makes them excellent for incorporation into wearable motion detection systems [19, 20]. These characteristics make TENGs a promising choice for developing self-powered and real-time sign language detection systems.

Recent advancements in wearable technologies, including devices equipped with TENGs and machine learning algorithms, have shown significant potential in this domain [21–23]. Smart wearables can accurately detect and translate sign language into text or speech in real time, facilitating immediate comprehension of the user's requirements [24–27]. Such systems not only enhance the responsiveness of emergency services but also promote inclusivity by integrating sign language interpretation capabilities directly into rescue and healthcare protocols [28, 29].

Chiu et al. developed a self-powered gesture-sensing device attached to the back of the hands that can identify hand movements by monitoring the TENG output signal in vertical contact separation mode [30]. Guidelines for translating sign language were developed to specify the correspondence between the motions and the associated English letters. Wen et al. designed a system that uses artificial intelligence to recognize and communicate in sign language. It consists of a virtual reality interface, a deep learning block, and sensor gloves using TENG [31]. The system correctly recognized twenty phrases and fifty words. The recognition results were projected into the virtual space as comprehensible text and sound to enable barrier-free communication between signers and non-signers. Lu et al. developed a novel lip-language decoding system (LLDS) that captures oral muscle movements using flexible, low-cost, and self-powered sensors and interprets the signals using a deep learning classifier [32]. To address the challenges of signal diversity, an enlarged recurrent neural network model based on a prototype with 94.5% test accuracy was used. Despite this, advanced sign language translation devices that use TENGs usually employ complex structures and material processing systems. Furthermore, these devices typically use materials that are relatively costly, less flexible, and provide limited comfort, restricting their usefulness. Therefore, an urgent need to develop a sign language detection system that is simple to develop, adaptable, and cost-effective to overcome the current challenges with sign language detection systems is required.

In this context, we have developed a self-powered, wearable smart glove made from fabric. This device is uniquely designed using flexible polyethylene (PE) fabric, low-cost copper/aluminum electrodes, and dual-geometry (circular and rectangular) TENG structures to capture signals from both finger joints and the back of the hand. The single-electrode mode TENG is circular type, making it perfect for adhesion in the fingertips, whereas the contact-separation mode-based TENG is rectangular, providing good adhesion to the upside of fingers.

Unlike previous studies, our system requires no external power supply, and the output signals are directly translated into digital text using a simple Python-based interface, eliminating the need for complex machine learning pipelines. After the smart-glove prototype was prepared, an emergency signal, like the "SOS" sign language, was performed, and the electrical signals were recorded. Then, those signals were processed by a signal processing algorithm using Python due to its flexibility, which allows for designing tailored algorithms that map unique TENG signals to specific letters, gestures, or actions based on application requirements. Importantly, this glove is specifically designed for emergency sign language communication, allowing rapid translation of key gestures into readable text for immediate understanding by non-signers. The text output, "SOS," can trigger automated emergency protocols, such as notifying first responders, activating alarms, or sending GPS coordinates along with the distress message. Moreover, the system's ability to process and respond in real-time ensures that TENG-based sign language detection systems are an

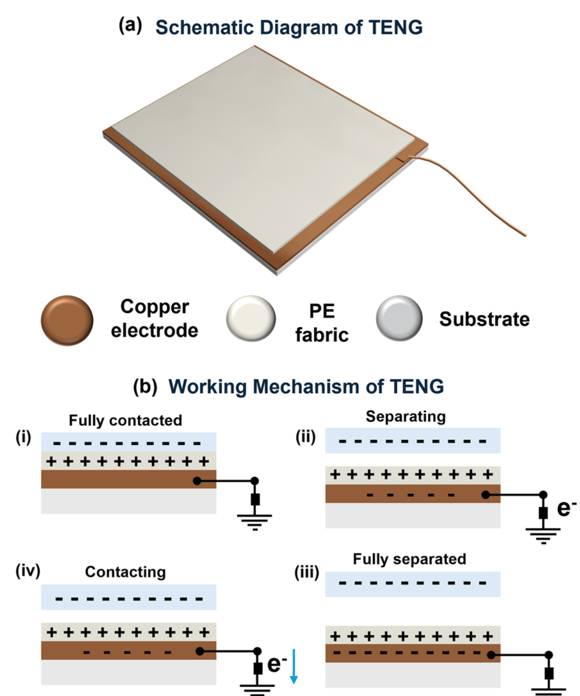

Fig. 1 **a** Schematic diagram of PE-TENG, **b** working mechanism of PE-TENG

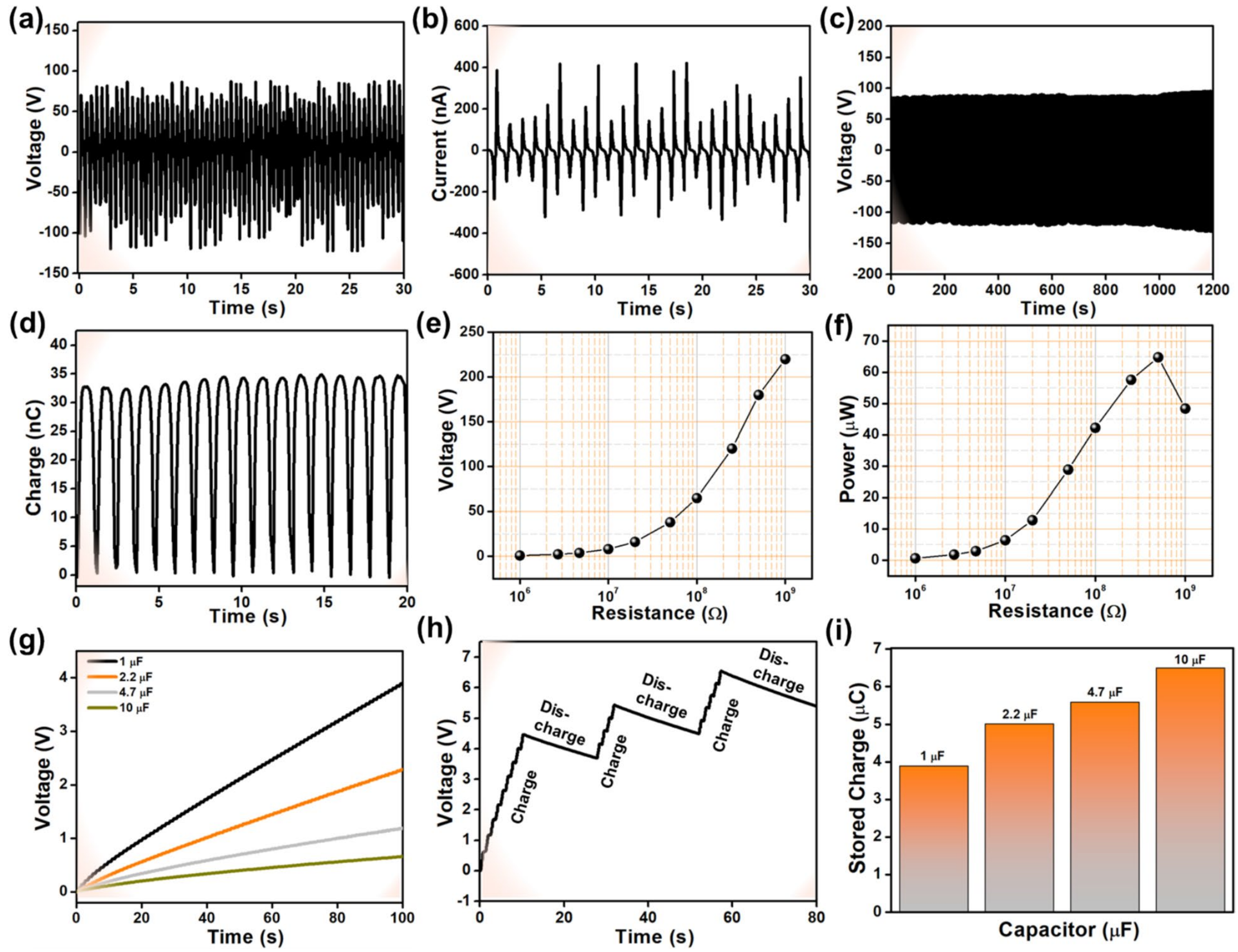

Fig. 2 **a**, **b** Voltage and current output of PE-TENG, **c** long-term stability test, **d** charge output of PE-TENG, **e**, **f** voltage and power output across various resistances, **g** charging of various capacitors, **h** charging-discharging curve, **i** stored charge in capacitors

essential tool in emergency communication situations. This approach offers a low-cost, sustainable, and scalable solution for real-time communication, with strong potential for deployment in critical care, disaster response, and assistive technologies.

Materials and methods

Materials

Latex gloves were purchased from Daiso, Korea. Polyethylene Fabric, conductive copper, and aluminum tapes were purchased from Alibaba, China.

Fabrication of TENG

Firstly, a single-electrode mode TENG was fabricated using a PET substrate, copper electrode, and PE fabric as the active material in a 4 cm × 4 cm square shape, then the circular single-electrode mode TENG was also fabricated, replacing the PET substrate with direct adhesion to the latex glove. The circular design was chosen to fit the fingertip shape for good adhesion. Then the contact-separation mode TENG was prepared in a rectangular shape using the copper electrode and PE as one layer, and aluminium as the opposite layer, having dimensions of 1 cm × 4 cm.

Results and discussion

The schematic diagram of the single-electrode mode square shape TENG is shown in Fig. 1a, which is made up of a PET substrate, copper electrode, and PE fabric as an active layer. The working mechanism of the PE-TENG is based on the combined effect of triboelectricity and electrostatic induction, as shown in Fig. 1b. At the initial state (i), there is no charge generation in the electrode when two triboelectric layers (PE and latex glove) are in contact. The electrostatic induction process causes positive charges to be induced on the electrode layer when

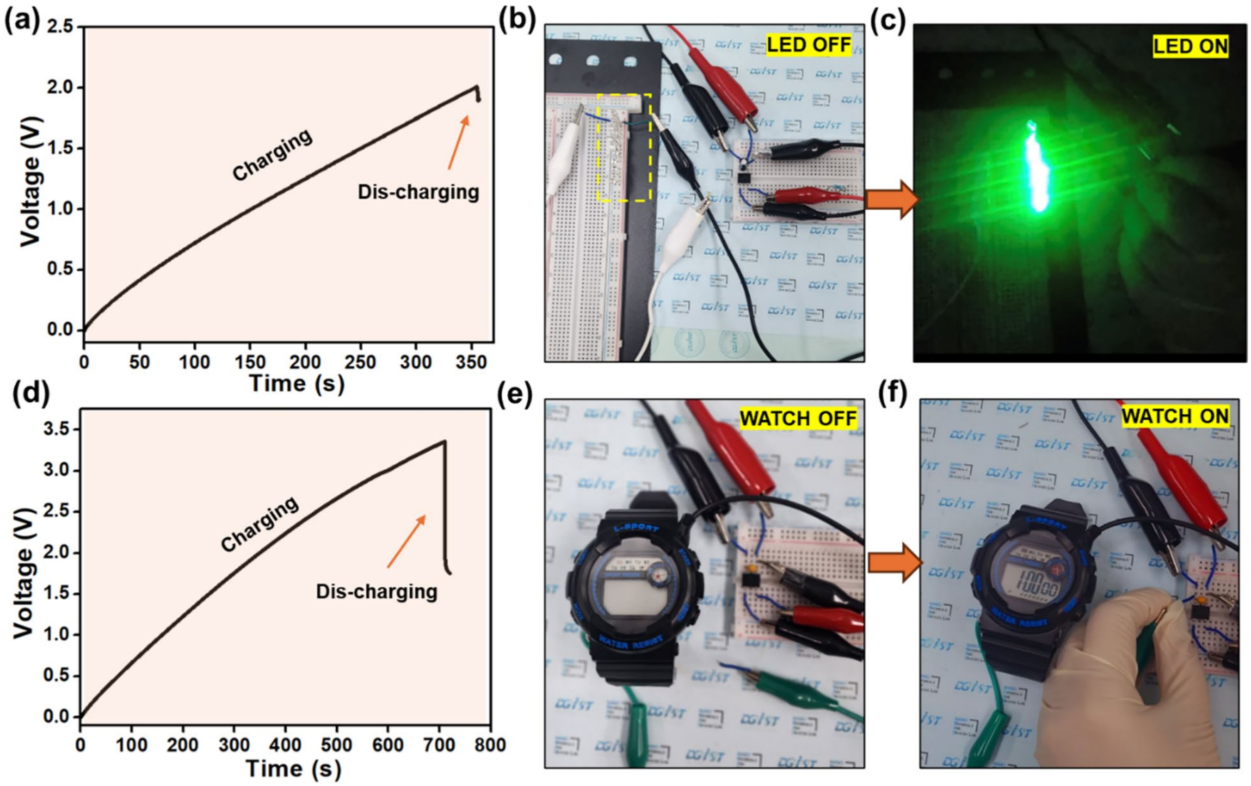

Fig. 3 **a** Charging a 10 μF capacitor, **b** digital image of LED OFF, **c** digital image of LED ON, **d** charging a 10 μF capacitor, **e** digital image of wristwatch OFF, **f** digital image of wristwatch ON

the two layers begin to separate (ii). An electrical current is produced when an electron begins to move due to the potential difference between the ground and the electrode layer. An electrical equilibrium stage is reached (iii), and the electrons stop moving when the two triboelectric layers are completely separated. As the PE layer again starts to contact the free-moving layer, electrons flow inversely from the electrode to the ground, making a charge balance state (iv). When the active layer fully contacts the free-moving layer, charge neutralization occurs. This period of the process leads to the generation of peak-to-peak electrical output. Supplementary Figure S1 (Fig. S1) shows the SEM and EDS spectra of the PE fabric. Elemental maps of carbon and oxygen were also provided to confirm the surface composition of the PE fabric employed as the active triboelectric layer. Since PE is a hydrocarbon-based polymer, its primary components are carbon atoms, with a small amount of oxygen added by surface oxidation to the atmosphere [33, 34]. When combined with more electronegative materials like aluminum, these elements show a non-polar, electron-donating surface that is essential to the triboelectric charging process [35]. Thus, confirming their presence supports the suitability of PE fabric as a tribopositive layer.

The measured contact angle of 91.37° in Fig. S2 indicates that the PE fabric possesses a moderately hydrophobic surface. This characteristic is particularly advantageous for triboelectric applications, as hydrophobic surfaces are less prone to moisture adsorption, making them less affected by ambient humidity. Since humidity can significantly alter surface charge density and lead to charge leakage [36, 37], the hydrophobic nature of the PE layer helps to stabilize and enhance the TENG output under varying environmental conditions.

The electrical output of the PE-TENG is shown in Fig. 2. The voltage and current of the PE-TENG shown in Fig. 2a, b are 220 V and 750 nA, respectively. The stability of the PE-TENG is demonstrated in Fig. 2c, where the voltage output was recorded for 1200 s, making the device ideal for long-term operations. Figure 2d shows the charge value of PE-TENG, which is 34 nC. The voltage of the PE-TENG was recorded using various load resistances, as shown in Fig. 2e. Here, the voltage increased while increasing the resistance following Ohm's law ($V = IR$), where V is voltage, I is current, and R is resistance. The power of the PE-TENG device was also calculated using the formula $P = V^2/R$. The highest power of the PE-TENG is 65 μW at 500 MΩ resistance,

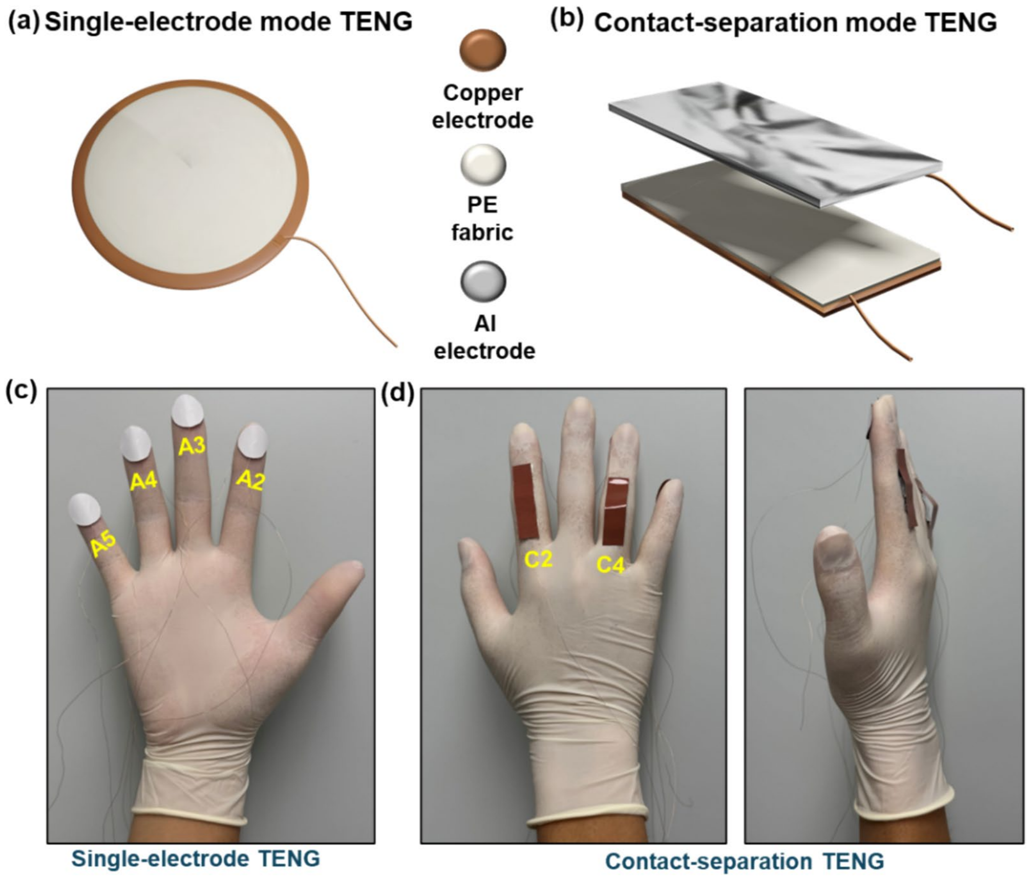

Fig. 4 **a** Schematic image of single-electrode mode-based circular TENG, **b** schematic image of contact-separation mode-based rectangular TENG, **c** digital image of TENG attached smart glove and the channels

as shown in Fig. 2f. Various capacitors (1, 2.2, 4.7, 10 μF) were also charged using the PE-TENG as demonstrated in Fig. 2g. A bridge rectifier was used to convert the AC signal of TENG to a DC signal. The charge–discharge behavior of the 1 μF capacitor using the PE-TENG is also shown in Fig. 2h. These several cycles of charging and discharging confirm a stable electrical output of the PE-TENG. The stored charge was calculated for each capacitor, as shown in Fig. 2i. The formula utilized for the calculation of charge is Q = CV (where C = capacitance and V = voltage). The PE-TENG device was also used to charge a 10 μF capacitor to glow 8 LEDs and to power a digital watch, as shown in Fig. 3a–f. The video demonstration of powering a digital watch is shown in Supplementary Video 1 (Video S1).

Figure 4a, b shows the schematic diagram of the wearable single-electrode TENG and contact-separation mode TENG and its layers. Figure 4c, d shows the digital image of the TENGs attached to the glove in different positions named A2 channel (index fingertip), A3 channel (middle fingertip), A4 channel (ring fingertip), A5 channel (little fingertip), C2 channel (backside of index finger), and C4 channel (backside of ring finger). These positions to attach the TENGs are completely customizable for sign-language detections. But here, the TENGs were attached in those positions to detect the common emergency sign language "SOS". The digital image of the front view, side view, and back view while doing the "S" and "O" signals is shown in Fig. 5a, b. For the circular single-electrode PE-TENG, the latex glove acted as the opposite free-moving layer.

To detect the "SOS" signal, individual finger TENG outputs were collected. Fig. S3 shows the individual output for "S" and "O" signals generated using individual fingers of A2 channel (a, b), A3 channel (c, d), A4 channel (e, f), and A5 channel (g, h), respectively. In comparison, Fig. S4 shows the individual output of the "S" and "O" signals generated using the finger C2 channel (a, b) and C4 channel (c, d), respectively. The schematic image of the collected signal from the individual fingers and the electrical output of the signal for "SOS" is shown in Figs. 6 and 7. Then, the threshold voltage for each channel was checked.

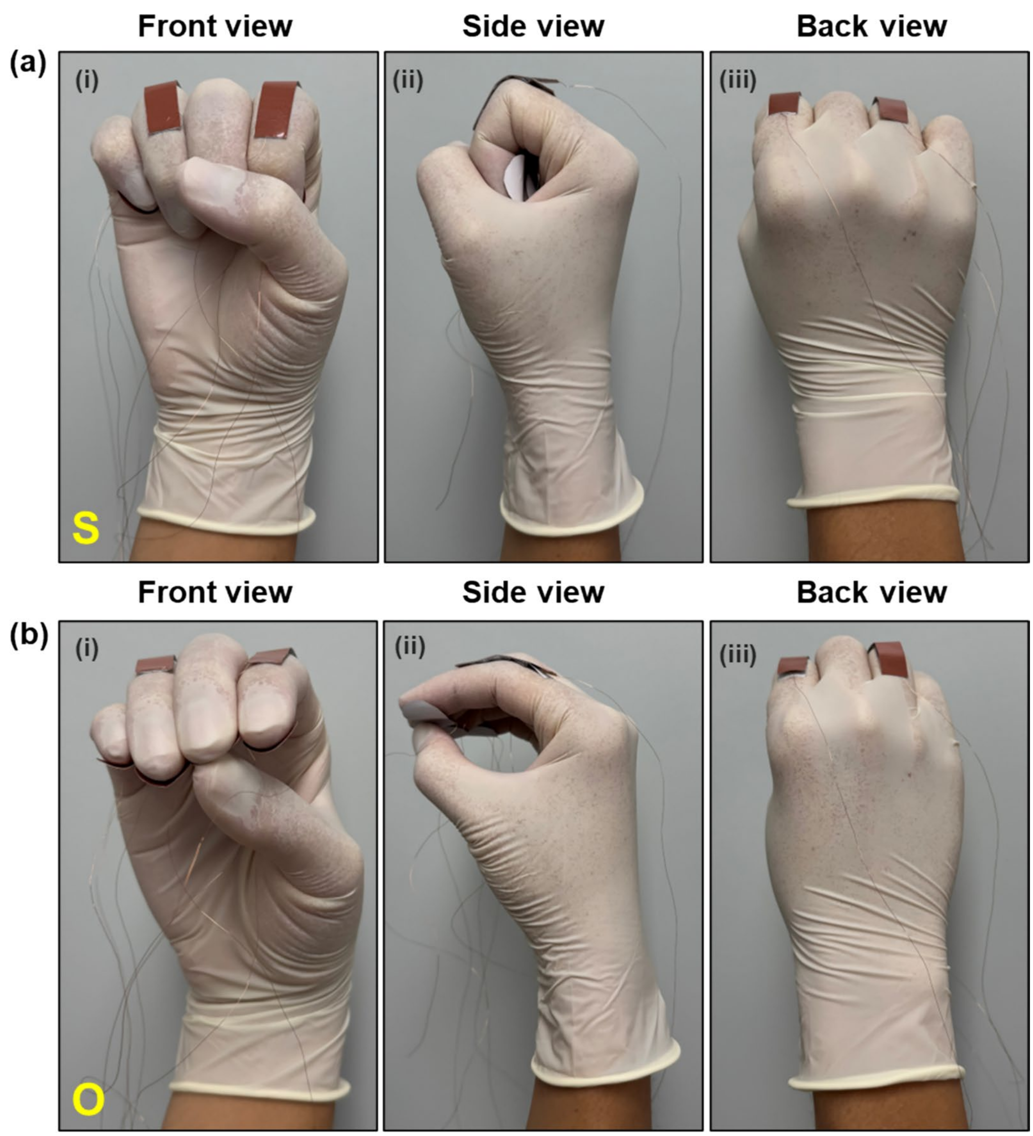

Fig. 5 Digital image of different views of hand gestures relating to **a** "S" and **b** "O"

In our approach, the threshold voltage was selected through a simple empirical process tailored to the experimental setup. The raw signal was divided into non-overlapping windows of fixed length (20 samples). This window size was chosen based on the average duration of a single sign gesture observed during controlled trials. For each window, the maximum signal value was extracted. The mean of these maximum values across all windows was then calculated. Finally, the threshold voltage was set to half of this mean value. This empirical division by two helped suppress false positives from background noise, while still preserving gesture peaks. The factor of 2 was chosen after observing that it provided the best trade-off between noise rejection and gesture sensitivity in our controlled setting.

Then, the sign language was performed, and the electrical signals were collected and then transformed into digital signals using Python, where signal < Vth» signal = 0, signal > Vth» signal = 1 value was set. Then the features were extracted, and the channel's outputs were combined and converted to the output recognized sign "SOS." The block diagram of the whole process is shown in Fig. S5.

The combined digital output of 6 signal channels is shown in Fig. 8a. The digital image of the gesture

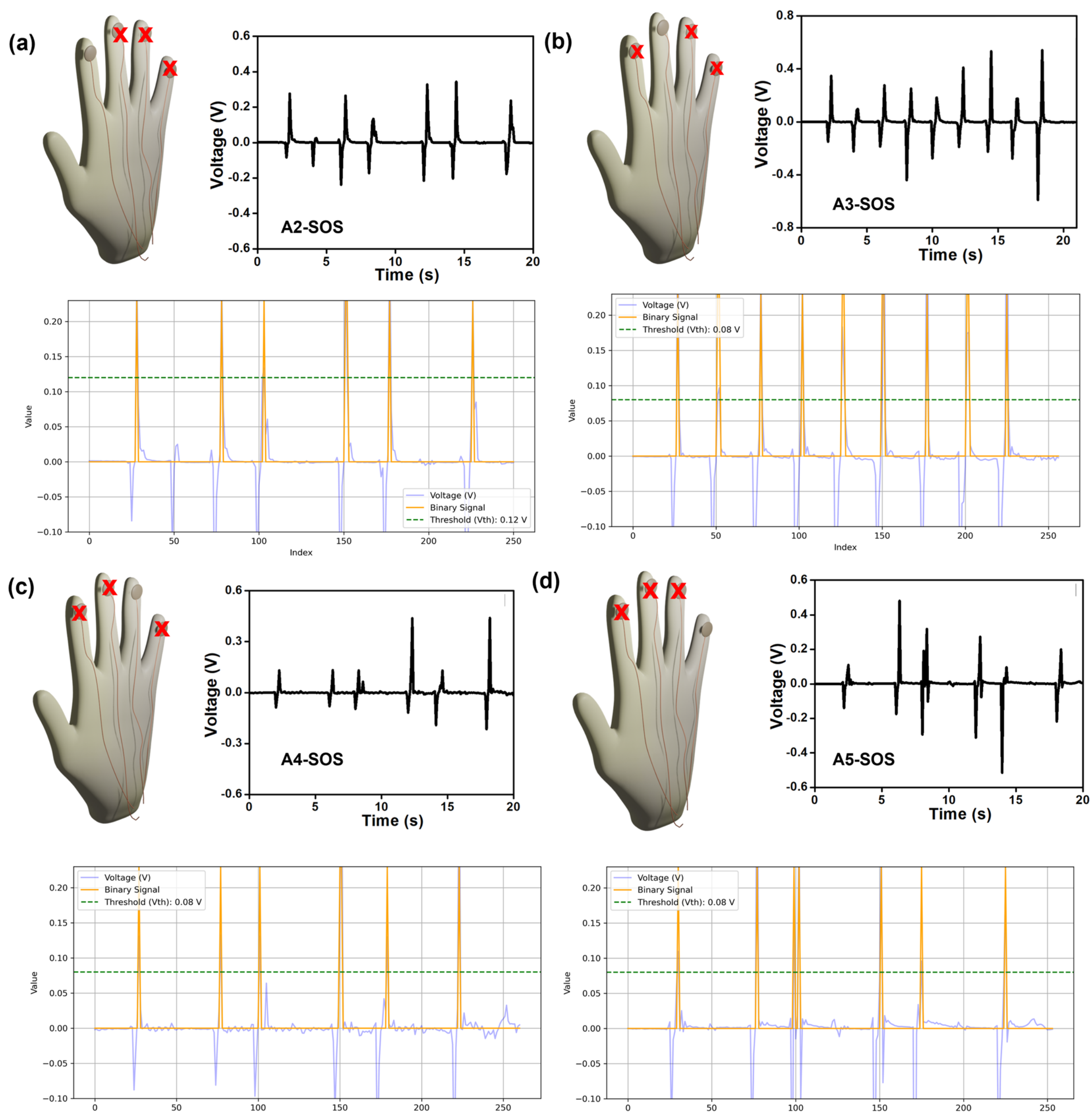

Fig. 6 Electrical outputs and setting threshold value using A2–A5 channels using circular TENG

regarding the S–O–S signal is shown in Fig. 8b. Finally, the electrical signal can be converted to text output and displayed on the screen using signal processing by Python and a graphical user interface. The video demonstration of the electrical signals converting into text signals is shown in Video S2. A comparison table based on various TENG device-based sign language detection is provided in Table S1. The smart glove-TENG-based device, combined with the signal processing technique for sign language recognition, shows a potential prototype of a future smart sign language recognition and communication system in any emergency for people who can't speak or hear. The text translation of the sign language using a battery-free, easy-to-fabricate, tailorable device enables the non-signer to understand in real-time and take meaningful actions immediately.

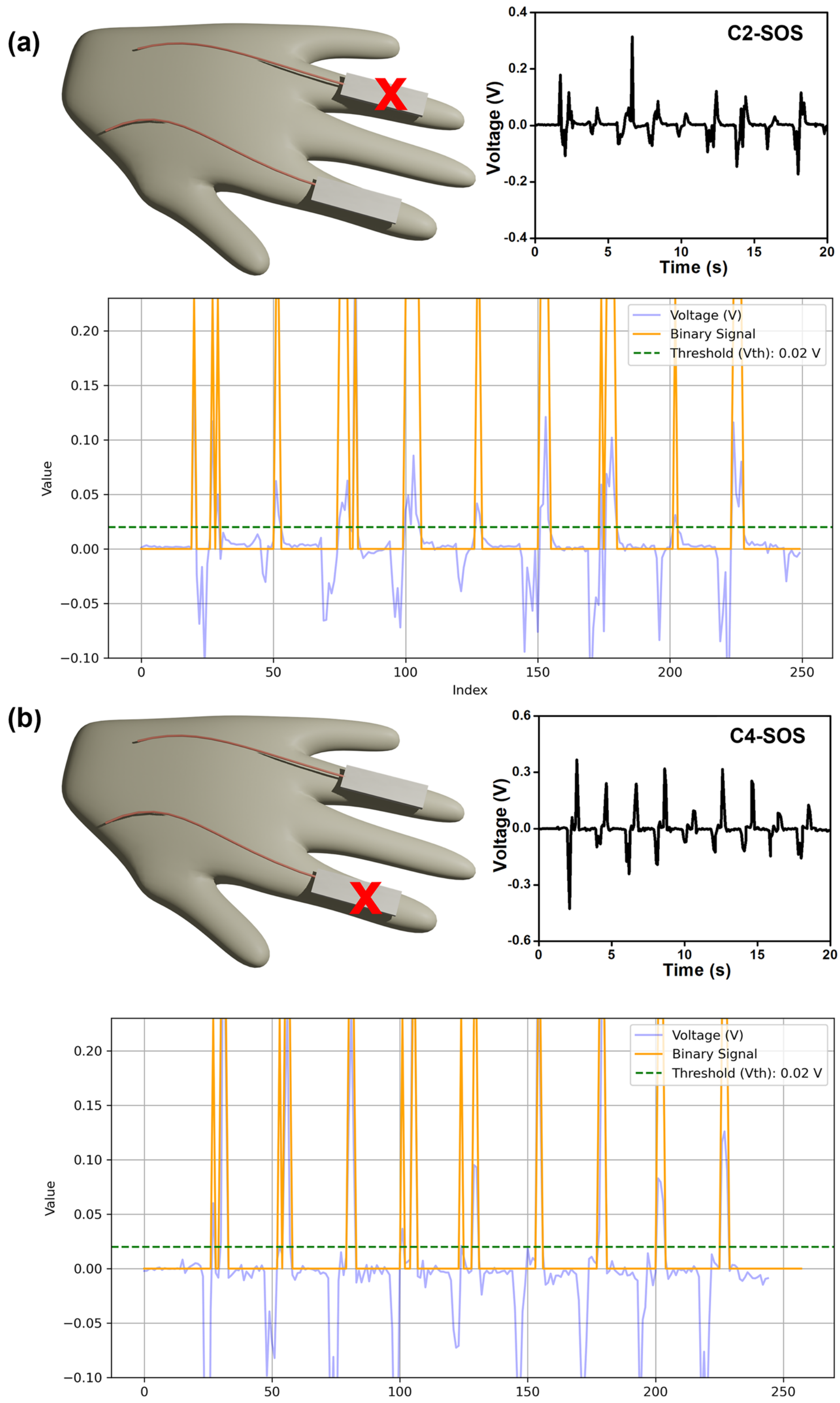

Fig. 7 Electrical outputs and setting threshold value using C2–C4 channels using rectangular TENG

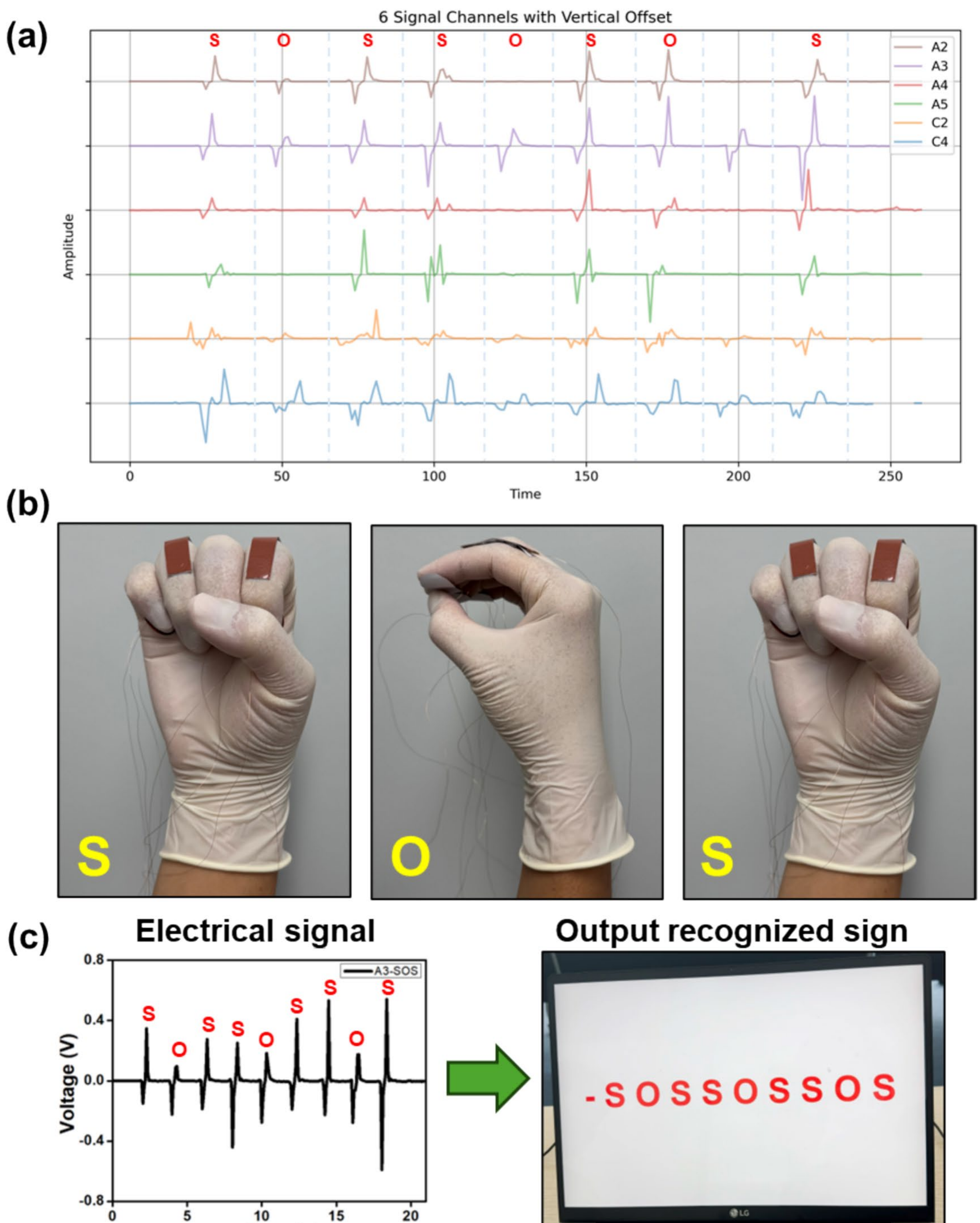

Fig. 8 **a** Combined electrical output of 6 channels in a vertical offset, **b** digital image of hand gesture making the sign language word "SOS", **c** translation of electrical signal to words using Python

Conclusion

In this paper, the applicability of a self-powered sign-language detection system using smart-glove-based TENG systems (single-electrode and contact-separation mode) was demonstrated. The active layer of the TENG contains PE, which is hydrophobic in nature, copper electrodes, and latex gloves as the opposite free-moving layer. The TENG was designed to be circular and rectangular to perfectly fit several positions of the fingertips and the backside of fingers as individual channels. Since PE fabric serves as an active layer, these TENG devices can efficiently harvest biomechanical energy from finger motions while ensuring finger comfort and excellent stability. The electrical outputs by performing the sign language gestures were collected, followed by setting the threshold values and converting them into digital signals using the signal processing technique Python. Then, the signal features were extracted, and outputs of each channel were combined, and the electrical signals were translated to text output recognized signs. This sign-language detection based on the TENG system is completely tailorable, easy to fabricate, low-cost, and wearable. The emergency sign languages can be easily translated into text signals and can be recognized by non-signers, and take immediate action for the required scenarios.

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s40486-025-00231-7.

Supplementary Material 1.

Supplementary Material 2.

Supplementary Material 3.

Author contributions

Hyeonggeun KIM: conceptualization, writing-original draft; Ingyu LEE: conceptualization, writing-original draft; Swati PANDA: writing-original draft, visualization; Sugato HAJRA: writing- editing, visualization; ByeongJun JEONG: visualization; Jeonggyu SEO: analysis, Kushal Ruthvik KAJA: writing- editing, visualization, Mohamed A. BELAL: formal analysis, visualization; Venkateswaran VIVEKANANTHAN: resources, writing-editing; Hoe Joon KIM: supervision, funding acquisition, writing-editing.

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Data availability

No datasets were generated or analysed during the current study.

Declarations

Competing interests

The authors declare no competing interests.

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