

Multilanguage-handwriting self-powered recognition based on triboelectric nanogenerator enabled machine learning

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ABSTRACT

Handwriting signature is widely used and the main challenge for handwriting recognition is how to obtain comprehensive handwriting information. Triboelectric nanogenerator is sensitive to external triggering force and can be used to record personal handwriting signals and associated characteristics. In this work, micro/nano structure textured TENG acting as a smart self-powered handwriting pad is developed and its effectiveness for handwriting recognition is demonstrated. Three individuals' handwriting signals of English words, Chinese characters and Arabic numerals are acquired by leaf-inspired TENG, and the other three people's handwriting signals of English sentences and the corresponding Chinese sentences are obtained by cylindrical microstructured PDMS based TENG, and these signals exhibit unique features. Combined with the machine learning method, the people's handwriting was successfully identified. The classification accuracies of 99.66%, 93.63%, 91.36%, 99.05%, and 97.73% were reached for English words, Arabic numerals, Chinese characters, English sentences, and the corresponding Chinese sentences, respectively. The results strongly suggested that the textured TENG exhibited great potential in personal handwriting signature identification, security defense, and private information protection applications.

1. Introduction

Handwriting signature is one of the most important personal behavioral biometric characteristics and occupies a very special place in the wide set of biometric. Meanwhile, the handwriting signature is widely used in a variety of civilian applications to authenticate individuals for enhanced security and privacy [1,2]. According to the acquisition approach, signatures are divided into offline and online. In offline, signatures are scanned and stored as grayscale or binary images, while in online, sequential information (e.g. x-y positions, velocity,

acceleration, pressure, and pen inclination) describes signatures [3]. In the online approach, specialized hardware such as a digitizing tablet or electronic pens with different sensors is used to capture the velocity, acceleration, pen inclination, and writing forces of pen movements simultaneously [4]. The design of handwriting signature verification systems (HSVS) based on the offline mode is more difficult compared to the online mode since many desirable characteristics such as the velocity, the pressure, and so on are not available during the acquisition [5]. The verification system depends on the features selected from the signature and generally, online signature verification systems have

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higher accuracy. Whereas the performance drops considerably in offline modes and big losses were caused due to the forgery signature [6]. However, the offline signature is more widely used in daily life due to its easy access and low cost. Therefore, it remains an open challenge in handwriting signature verification and the key is developing new record methods to obtain comprehensive handwriting information including position, velocity, acceleration, pressure, force, direction, and pen inclination during writing at low cost.

In 2012, Wang's group invents triboelectric nanogenerator (TENG, i.e. Wang Generator) and its working principle is the coupling of triboelectrification and electrostatic induction [7–10]. The fundamental theory of nanogenerators starting from Maxwell equations and nanogenerators are the applications of Maxwell's displacement current in energy and sensors [11–15]. Since it was born, TENG has attracted a lot of attention and numerous wonderful works have been done [16–23]. The output electrical signal of TENGs is directly related to the external mechanical excitation, and thus TENGs are capable to detect the pressure, strain, velocity, position, and relative displacement. Due to its easy fabrication, low cost, and high sensitivity, TENGs have been successfully used to measure pressure [24,25], touch [26,27], eye motion [28], velocity [29], vibration [30] and body motion [31]. Moreover, it has presented that TENG can harvest typing energy and intelligent keyboard based on TENG array enabled authentication and identification [32–34]. Some great works have been done and demonstrated that TENG could apply in human-machine interfaces (HMI) to achieving the high-precision and real-time interface [35], and build a new generation of auditory systems for meeting the challenges in social robotics [36]. Lee et al. demonstrated that Combining TENG based self-powered sensor with machining learning method, low-cost and advanced human-machine interaction could be achieved [37], and highly accurate virtual reality/augmented reality (VR/AR) controls could come true [38]. These previous works inspired us that TENG may be an ideal device that can collect and record abundant writing behavior information including writing force, velocity, direction and inclination. Therefore, the handwriting signal acquired by TENGs may dramatically improve the classification accuracy rate of offline handwriting recognition and further reduce the economic losses owing to forgery signature.

The surface texture technique is considered as one of the most important ways to enhance the output performance of TENG and improve the sensitivity of TENG based self-powered sensors [39–41]. However, the conventional micro/nano-structure patterning process involves sophisticated fabrication procedures, such as lithography, photolithography, nanoimprinting lithography and laser interference lithography, which are time-consuming and high-cost [42,43]. As one of the most abundant biomass sources on earth, leaves with rich natural micro/nano-structure pave a new avenue to easily make large-scale leaf-inspired micro/nano-structures on the PDMS with low cost to harvest the widely distributed energies in nature. Bioinspired TENGs are developed by replicating the surface morphology of natural *C. zebrina* leaf burrs and the triboelectric effects were enhanced due to the interlocking microstructures on tribo-layers [44], however, the differences between various natural leaves and their effects on TENG's performance were ignored. The selection of optimal leaves for enhancing the output performance of Wang Generator is still an open challenge and worthy of addressing. Also, the technology for rapidly fabricating large scale microstructure is also an issue that still needs to be explored.

Here, four kinds of leaves were selected and their micro/nano-structures that present unique and superior functions formed via long-term natural selection process were replicated on PDMS. Cylindrical microstructure PDMS was fabricated by using a casting method that can rapidly make large scale microstructure sample at very low cost. Micro/nano-structures contact-separation mode TENGs were fabricated and their output performance was measured. Based on their output performance and the characterization of the leaf-inspired microstructures, the mechanisms of leaf-inspired microstructures on the TENG's performance were discussed. Moreover, the TENG with optimal leaf-inspired

microstructure was employed as a smart self-powered handwriting pad to record three persons' handwriting signals of writing different English words, Arabic numerals and Chinese characters. Then the handwriting information obtained by the leaf-inspired TENG was applied to recognize the handwriting of the three people combining with signal processing and machine learning technology. With the novelty recording method of the micro/nano surface structures based TENG, high recognition rates were acquired both for the three kinds of characters and the two kinds of wide used sentences. It implies that the micro/nano surface structures based TENG could be used as a smart self-powered handwriting pad in personal handwriting signature identification, security defense and private information protection applications.

2. Experimental section

2.1. Fabrication of textured PDMS

Fresh-picked *bischofia polycarpa* (BPO), *baubinia purpurea* (BPU), *plumeria rubra* (PR) and *crape myrtle* (CM) leaves were cleaned with ethyl alcohol and deionized water bath successively by the ultrasonic wave and then cut into pieces 6 cm by 6 cm in size and attached to PMMA as flatly as possible. The PDMS solution (Sylgard 184, Dow Corning Co., Ltd) was prepared by mixing the PDMS base with curing agent in 10:1 proportion and stirring for 5 min. Thereafter the prepared PDMS solution was placed into a vacuum chamber for 30 min to eliminate air bubbles and stored in the refrigerator for 2 h. Next, the PDMS solution was cast on the rectangular leaf template and put into a vacuum chamber curing at 85 °C for 30 min. After the temperature dropped to room temperature, the template was taken out and the PDMS was peeled off from the leaves, making the micro/nano-structure be duplicated on the PDMS. The cylindrical microstructure PDMS sample was fabricated by using a casting method. Combined stamping technology with the casting method, the microstructure PDMS samples can be rapidly and large-scale fabricated with low cost. The details of the fabrication process are identical with the procedure for fabricating the micro/nano-structures PDMS samples inspired by leaves. An identical thickness PDMS was very important and the heights of the molds for casting textured PDMS layers were strictly controlled to obtain the PDMS layers with an identical thickness of 0.25 cm.

2.2. Fabrication of TENGs

A layer of conductive copper tape was attached on the backside of bioinspired PDMS as the bottom electrode. Then the PDMS was attached to a piece of PMMA as the bottom triboelectric part. A piece of thin copper film was attached to PMMA and the copper film plays a dual role, namely, the triboelectric layer and the top electrode. The top and bottom triboelectric layers were connected by using four low *k* springs and TENGs were fabricated. The spacing between the up part and the bottom part was 0.6 cm.

2.3. Characterization and electrical measurement

The surface morphology of leaf-inspired PDMS was measured by using confocal laser scanning microscopy (VK-X200 series, Keyence). The electrical output of leaf-inspired TENG was measured by using a low noise current preamplifier (SR570, Stanford Research System) with computer measurement software written in Labview and the TENG was triggered by a 5 N normal force and the measurements were conducted with a temperature of 25 ± 1 °C and relative humidity of $60 \pm 5\%$ RH. The three individuals wrote English words, Chinese characters and Arabic numerals on the BPO leaf-inspired smart self-powered handwriting pad with a fine marking pen and their handwriting signals were acquired by using the low noise current preamplifier under a temperature of 25 ± 1 °C and the relative humidity of $60 \pm 5\%$ RH. The other three people wrote English sentences and Chinese sentences on the

cylindrical microstructure PDMS based TENG with a ballpoint pen and the signals were recorded by using the low noise current preamplifier under a temperature of 22 ± 1 °C and relative humidity of $25 \pm 5\%$ RH.

3. Results and discussion

Fig. 1 shows a schematic illustration of the procedure for fabricating textured PDMS samples and its micro/nano-structures. Four kinds of leaves were selected, namely, *bischofia polycarpa* (BPO), *bauhinia purpurea* (BPU), *plumeria rubra* (PR) and *crape myrtle* (CM), their micro/nano-structures were replicated on PDMS, as shown in Fig. 1a. The replicating procedure consisted of four main steps: select perfect leaves and clean them with ethyl alcohol and deionized water bath successively by ultrasonic wave (step I). Subsequently, cut the selected leaves into a square with a length of 6 cm (step II). Thereafter, put the tailored leaves into the prepared mold and the mixture of PDMS base and cross-linker was poured onto the leaf and cured at a temperature of 85 °C for 60 min in a vacuum oven (step III). Finally, took the mold out and peeled the PDMS off from the leaves, flexible leaf-mimicking PDMS with rich micro/nano-structure was obtained (step IV). Fig. 1b shows the fabricating processes of cylindrical microstructure PDMS samples by using the casting method. Combined stamping technology with the casting method, the microstructure PDMS samples can be rapidly and large scale fabricated with low cost. Fig. 1c shows the surface morphologies of the PDMS samples that the surface micro/nano-structures were replicated from the front surface of the four selected leaves. Fig. 1(c1) is the PDMS with the micro/nano-structure that duplicated

from the front surface of BPO. The uniform strip-shaped microstructure could be clearly seen on the BPO-inspired PDMS surface and the width and length of the strips are about 10 μm and 35 μm , respectively. Fig. 1(c2) shows the BPU-inspired PDMS and it possessed a rich micro/nano structure on the surface. Especially, a large number of spherical structures with the diameter size ranging from approximately 0.3 μm –4 μm were randomly distributed on the PR-inspired PDMS. Fig. 1(c3) shows the PR-inspired PDMS with different sizes of raised micro/nano-structure evenly distributed on the surface. As shown in Fig. 1(c4), various raised and cupped micro/nano-structure can be clearly seen on the CM-inspired PDMS. The heights of the micro/nano structures of leaves inspired PDMS, as shown in Fig. S1, would affect the electrical output performance of the leaves micro/nano structures inspired TENG.

The working mechanism of the TENG is based on the coupling of triboelectrification and electrostatic induction, as shown in Fig. 2. At the initial state, the top and bottom triboelectric layers of leaf-inspired TENG was fully released and no charge was generated on their surfaces (Fig. 2aI). When the PDMS contacted with copper under an external mechanical force, due to their different electron affinities equal amount of induced positive and negative charges were generated on the contact surface of copper and PDMS (Fig. 2 aII). Then the external driving force released and the PDMS and copper were gradually separated. The separation motion induced a potential drop between the triboelectric layers and drove the electrons flow from the back electrode of PDMS to copper, generating a pulse current flowing from top electrode to bottom electrode (Fig. 2 aIII). The electrons would stop flowing until the gap distance between the triboelectric layers reached the

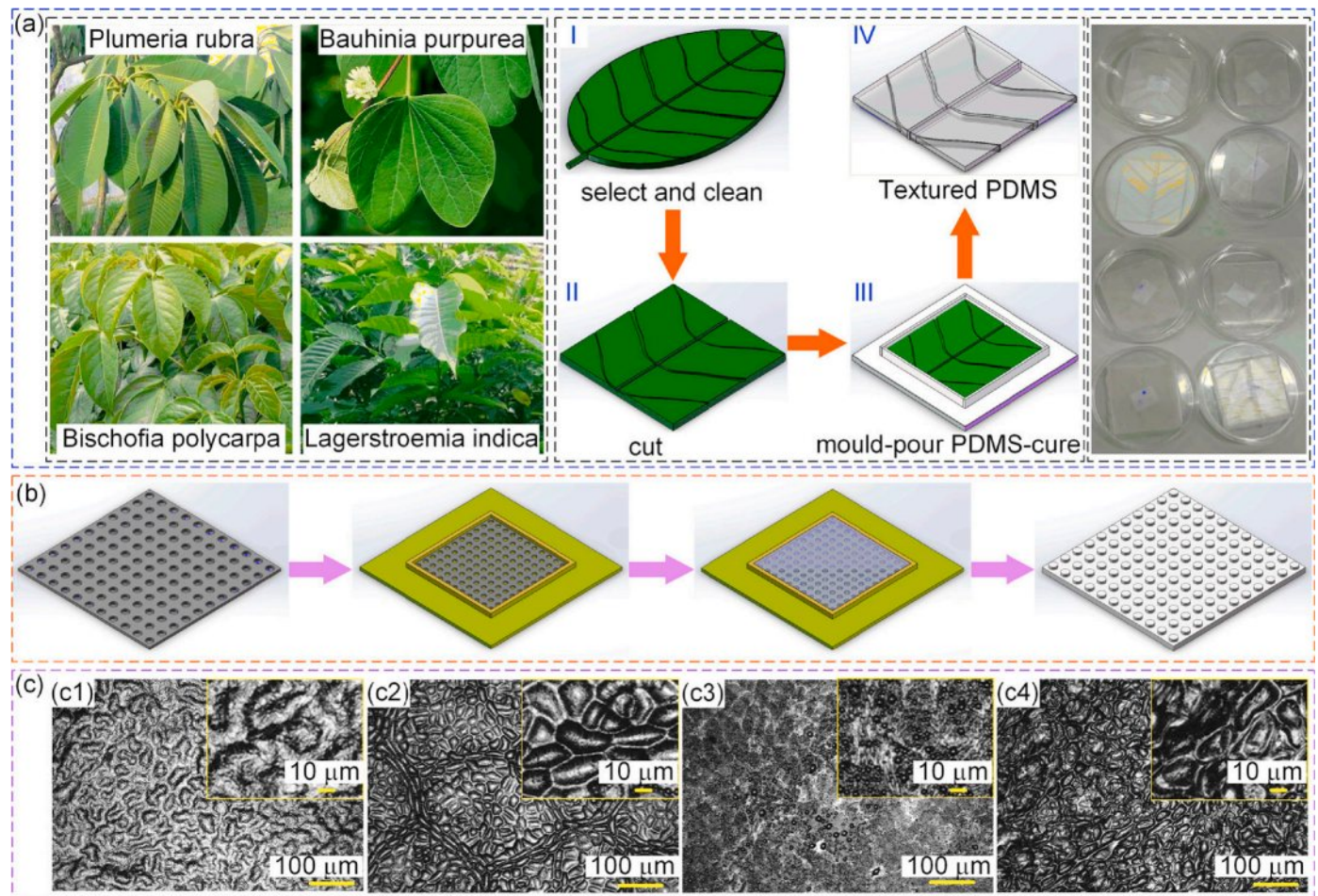


Fig. 1. The schematic illustration of the procedure for fabricating textured PDMS sample and its micro/nano-structures. (a) The procedure for replicating the micro/nano-structures of the selected leaves to the PDMS. (b) The fabricating processes of cylindrical microstructure PDMS by combing stamping and casting technology. (c) The surface morphologies of the PDMS samples that the micro/nano structures were replicated from the front surface of the four selected leaves.

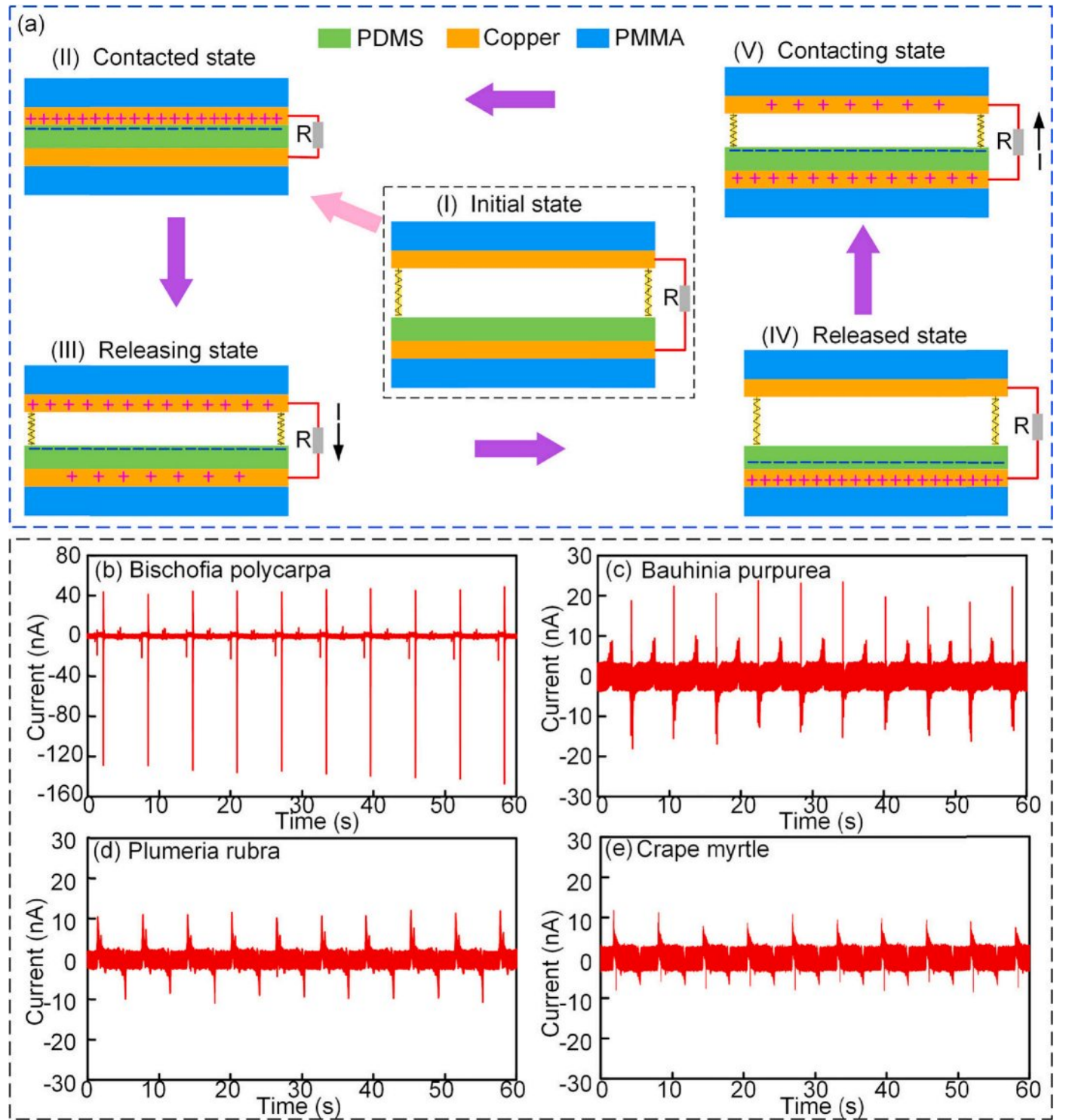


Fig. 2. The working mechanism and output currents of TENG. (a) Schematic illustration of the working principle of TENG. I: initial state; II: contacted state; III: releasing state; IV: released state; V: contacting state. (b) Short-circuit output current of BPO inspired TENG. (c) Short-circuit output current of BPU inspired TENG. (d) Short-circuit output current of PR inspired TENG. (e) Short-circuit output current of CM inspired TENG.

maximum and an electrical equilibrium was achieved while the TENG got into the fully released state (Fig. 2aIV). Then the PDMS and copper were approaching when the external force was applied again, the change of electric potential difference drove electrons flow from top electrode to bottom electrode until an electrostatic equilibrium state was formed again (Fig. 2aV). When the TENG was contacted and released periodically, an alternative current pulse was continuously generated. The handwriting forces of different individuals are different but the writing

force of adults mostly within 5 N [45–47]. Therefore, the performances of the leaf-inspired TENGs were measured under a driving normal force of 5 N in ambient condition. The measurements were repeated three times and the short-circuit output currents of BPO, BPU, PR and CM leaf-inspired TENG were shown in Fig. 2b–e, respectively. The output performances of TENGs exhibited good repeatability and the maximum short-circuit output current of the four TENGs reached 130 nA, 25 nA, 11 nA and 10 nA, respectively. It was noticed that the TENG with the

micro/nano-structures of BPO leaf exhibited the highest output performance, making it the best candidate for a smart self-powered handwriting pad to record the handwriting signal.

Fig. 3 shows the diagram of acquiring handwriting signals by using the TENG. The handwriting information recorded by the paper is stored as grayscale or binary images, as shown in Fig. 3a. Traditionally, for offline mode handwriting recognition and identification, the completed writing information is available as image and the handwriting data is converted to the digital format by scanning the writing on paper which is time-consuming and involves high cost. Fig. 3b shows the sketch of recording handwriting data by using the TENG based smart self-powered handwriting pad. For the abundant material choices, low cost and easy fabrication of TENG, the handwriting data could be acquired and saved as digital signal with a low cost. It could be clearly seen that the handwriting signals of different individuals' were acquired by the TENG and their handwriting signals exhibited unique features, which had huge advantages over traditional recording methods. The English words, Chinese characters and Arabic numerals are used by the most people all over the world and the handwriting signals of people writing these characters were acquired. Fig. 3c1-c3 show the handwriting signals of Li, Yang and Xie wrote the same English word "Advanced" on BPO leaf-inspired TENG based handwriting pad. Fig. 3d1-d3 show the handwriting signals of Li, Yang and Xie wrote the same Chinese characters "传感" which were recorded by the BPO leaf-inspired TENG based handwriting pad. Fig. 3e1-e3 show the handwriting signal of Li, Yang and Xie wrote the Arabic numerals "01" on the BPO leaf-inspired TENG based handwriting pad. Due to the difference among their writing pressure, velocity, acceleration and so on, it was clearly shown that their handwriting signals exhibited a large difference in time domain no matter what kind of characters they wrote. It could be found that, when the three people writing the same character, the number and amplitude of pulses in their handwriting signal exhibited a huge difference. That's because the TENG based handwriting pad could record the sequential handwriting signals which embodied the key information of individual handwriting habits of anyone, including x-y position, velocity, acceleration, pressure and pen vibration in the handwriting process. To further analyze the difference of their handwriting signals, their handwriting signals were converted from the time domain into the frequency domain. Fig. 3c1'-c3' show the energy spectral density of handwriting signals of Li, Yang and Xie for writing the English word "Advanced"; Fig. 3d1'-d3' give the energy spectral density of handwriting signals of Li, Yang and Xie for writing Chinese characters "传感"; Fig. 3e1'-e3' is the energy spectral density of handwriting signal when Li, Yang and Xie wrote Arabic numerals "01". It can be easily observed that, in the frequency domain, the spectrum components of each handwriting signal were also different, and the dominant components of the three individuals' handwriting signals appear in a different frequency band. It was also demonstrated that a huge difference in the energy spectral density of the three persons' handwriting signals for writing the same character. All the above unique features of their handwriting signals suggest that the TENG based handwriting pad is a killer that could be used for human handwriting signal recording, human handwriting recognition and identification.

Fig. 4 shows the application of the TENG based handwriting pad in handwriting recognition and identification. Though the handwriting signals of different people exhibited huge difference in time domain and frequency domain, it was very complex to recognize and identify the handwriting by directly using the time domain signal or frequency spectrums. Hence, it was necessary to further process the handwriting signal directly acquired by TENG and the data processing procedure was shown in Fig. 4a. The signal energy is a basic statistical feature that could represent the intensity of the signal and reflect the stored energy of the signal within a certain frequency range [48]. The energy spectrums of handwriting signals of the three people exhibited obvious difference and covered different useful frequency components, as shown in Fig. 3. Therefore, calculating the sub-band energy of the handwriting

signals was the best way to extract feature information of handwriting signal. The wavelet packet decomposition is a time-frequency analysis method and it could decompose the signal into different frequency components [49]. In this study, the wavelet packet decomposition method was employed to process the handwriting signals to extract the sub-band energy feature. The Meyer wavelet was selected as the wavelet basis function and the handwriting signal was decomposed into 3 layers to construct the feature data set, as shown in Fig. 4a II-III (The detailed spectrums and waveforms of handwriting signal components of English words, Chinese characters and Arabic numerals were shown in Figs. S2-S7). Then the principal component analysis (PCA) method was carried out to further reduce the dimensions of the feature data set to obtain the low-dimensional principal components with higher identification [50]. Herein, the first four principal components were used for handwriting identification and the cumulative contribution rate of them exceeded 90%, as shown in Fig. 4a-IV. The support vector machine (SVM) was developed in the 1990s based on the statistical learning theory, and it has excellent learning and strong generalization abilities and is widely used in pattern recognition for multi-classification problems, particularly suitable for data classification with small samples [51]. Basic SVM is only able to conduct a binary classification problem. For the multi-classification problem, some improved SVM models are put forward. The multi-classification model of SVM-based decision tree (SVM-DT) is a kind of improved SVM model for multi-classification and widely used due to its short training time and fast convergence. In this work, the number of handwriting signals does not exceed 100 and the handwriting signals of three people need to be classified, so SVM-DT is employed as the preferred classifier [52]. The radial basis function was selected as the kernel function, and the penalty parameter C and the kernel parameter σ were both set to the relatively moderate values (i. e. $C = 100$, $\sigma = 4$) for SVM-DT [53]. The handwriting recognition process which combining TENG with the machine learning method as shown in Fig. 4b. Here, the English word "Nano" was selected as an example to illustrate the process of handwriting recognition. Firstly, Li, Yang and Xie wrote the word "Nano" on the BPO leaf-inspired TENG based smart self-powered handwriting pad 100 times and their handwriting signals were recorded. Then, their handwriting signals were processed by using the signal processing method. Moreover, to validate the effectiveness of the handwriting recognition system combining TENG with machine learning method, the 10-fold cross-validation method was used for training and testing the SVM-DT, i.e., the nine-tenths of the sample data was used as training data to train the SVM-DT model and then the other one-tenth of the sample data were used as testing data to verify the recognition accuracy in each cycle repeated ten times. Fig. 4b clearly shows that all the testing data of the English word "Nano" is correctly recognized.

For further demonstrating the excellent performance of the handwriting recognition system based on TENG combining with machine learning, extra more and different kinds of characters were needed to be recognized and identified. Here, the English words "Nano", "Advanced", "TENG", "Energy" and "Sensor" were selected as the characters to be recognized and each word was written by Li, Yang and Xie 100 times, respectively; for Chinese characters, "能源", "摩擦", "纳米", "发电" and "传感" were chosen as the object to be recognized and they were written as the same way for 100 times; the Arabic numerals "01", "23", "45", "67" and "89" were selected as items to be classified and each of them was also conducted as the same scheme of the former two kinds of characters. Fig. 4c shows the recognition accuracies of the three individuals' handwriting of English words, Chinese characters and Arabic numerals. It was found that very high recognition accuracies were obtained by using the handwriting recognition method proposed in this paper. Among them, the English word exhibited the highest classification accuracy that all exceeded 99%, as shown in Fig. 4c1. The recognition accuracies of Arabic numerals and Chinese characters were relatively low, but the lowest accuracy of the number "89" also reached 83.25%, as shown in Fig. 4c2-c3. Fig. 4c4 displays the average

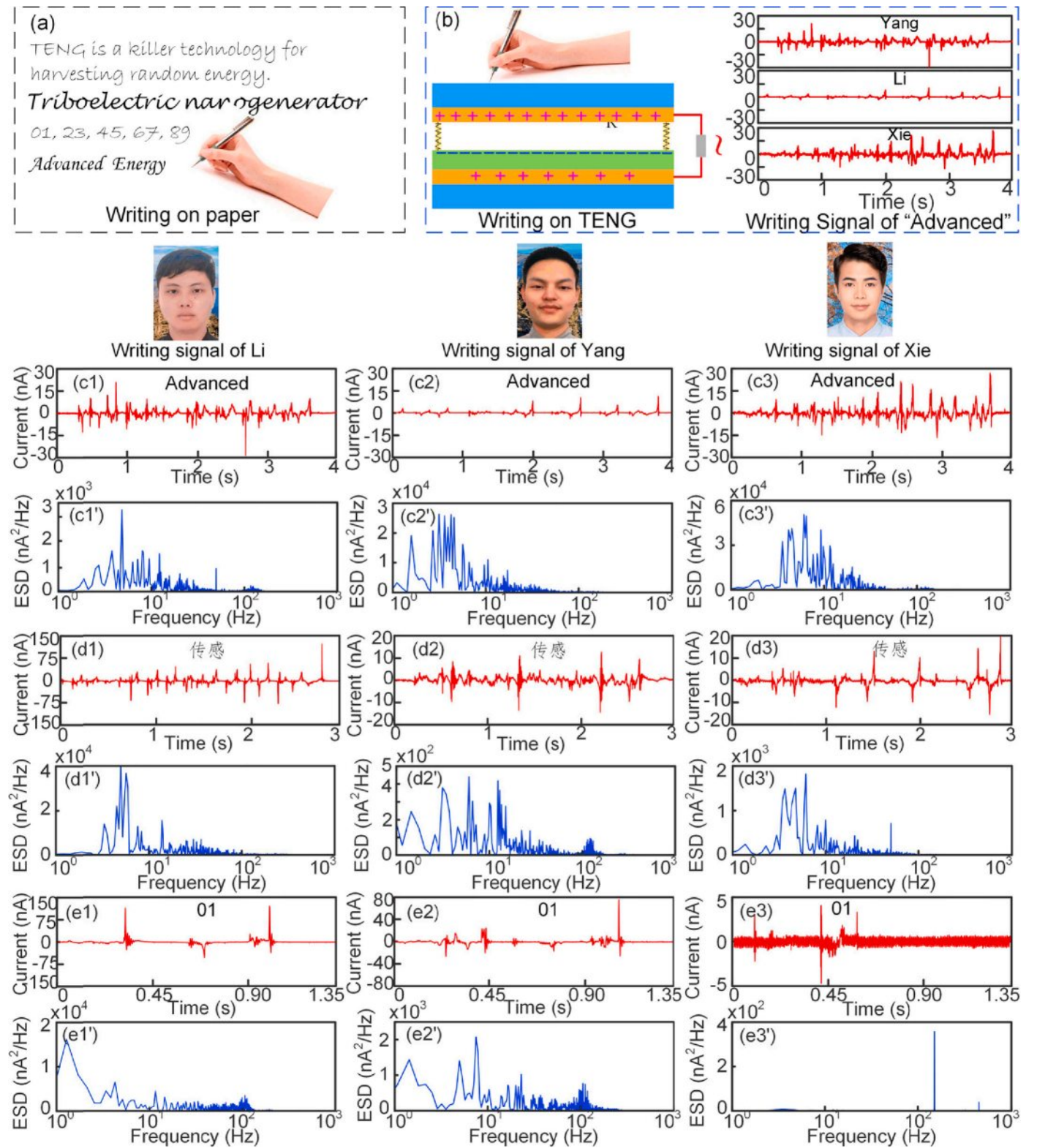


Fig. 3. The illustration of handwriting signals recorded by using BPO inspired TENG based handwriting pad. (a) Sketch of traditional handwriting on paper. (b) People's handwriting signal of the same words was recorded by using BPO inspired TENG. (c1-c3) The handwriting signal of Li, Yang and Xie corresponding to write the word "Advanced" on the BPO inspired TENG. (c1'-c3') The energy spectral density of handwriting signals for writing the word "Advanced". (d1-d3) The handwriting signal of Li, Yang and Xie corresponding to write the Chinese characters "传感" on the BPO inspired TENG. (d1'-d3') The energy spectral density of the handwriting signal of the Chinese characters "传感". (e1-e3) The handwriting signal of Li, Yang and Xie corresponding to write the Arabic numerals "01" on the BPO inspired TENG. (e1'-e3') The energy spectral density of the handwriting signal of the Arabic numerals "01".

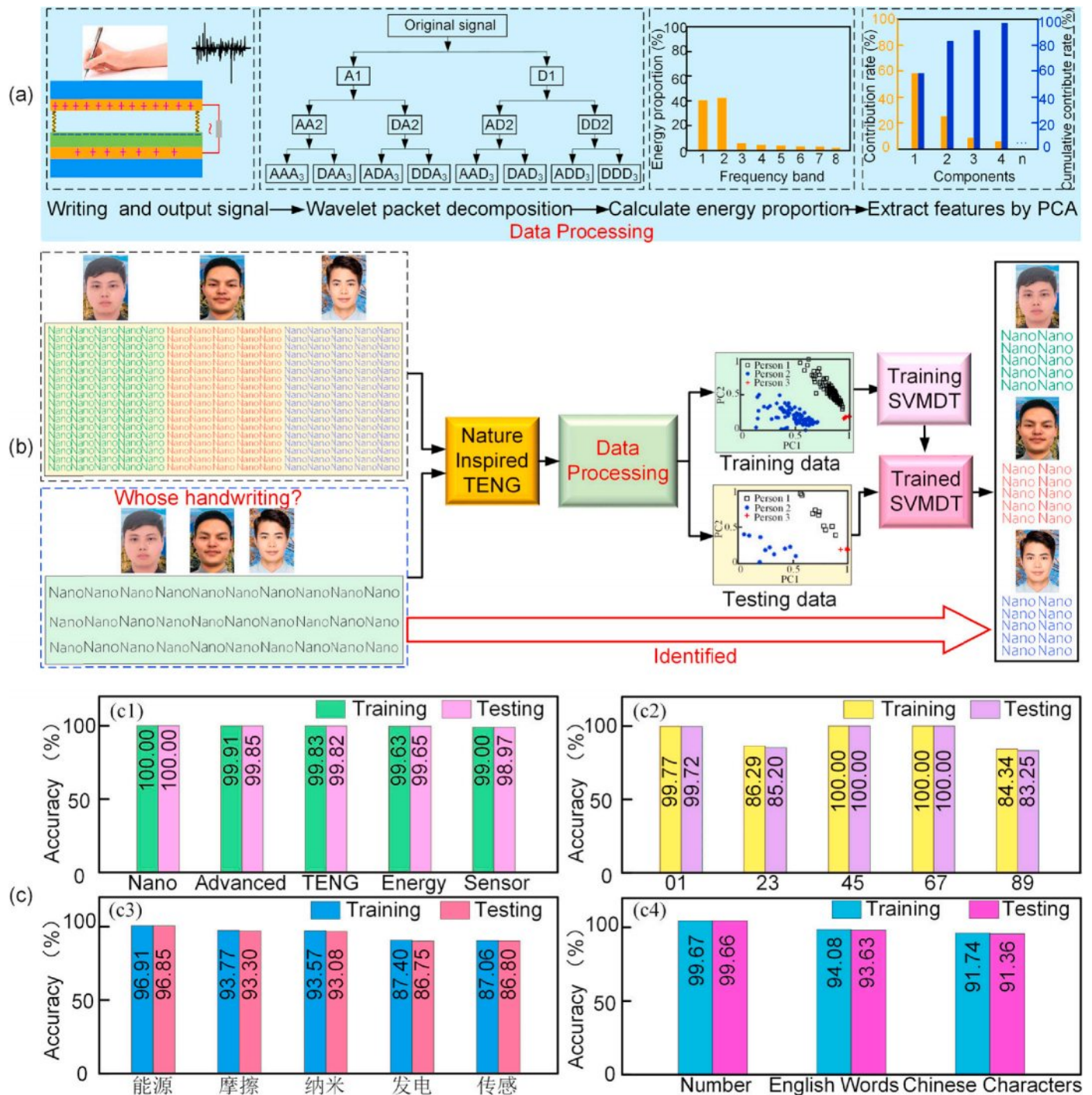


Fig. 4. Application of the leaf-inspired TENG in handwriting recognition and identification. (a) The data processing procedure of the handwriting signal was recorded by the leaf-inspired TENG. (b) Illustration of the handwriting recognition and identification process combined with leaf-inspired TENG and machine learning method. (c) The classification accuracies of the three individuals' handwriting of English words, Chinese characters and Arabic numerals.

classification accuracies of English words, Arabic numerals and Chinese characters. Although the classification accuracy of Chinese characters was the lowest among the three kinds of characters, it still reached 91.36%, which demonstrated that the method proposed in this study could effectively identify the characters written by different people. All the above results revealed that, by using the leaf-inspired TENG combined with advanced signal processing techniques and machine learning method, the handwriting of different people could be effectively analyzed and accurately recognized no matter what kind of the characters.

One of the great expectations of the public is that the textured TENG with low cost can still work well for handwriting identification application in more sophisticated situation. Therefore, the application of the TENG that consists of thin copper and cylindrical microstructure PDMS in sentences handwriting recognition was conducted. Fig. 5 shows the diagram of the application of the cylindrical microstructure PDMS based TENG in sentences handwriting identification. Fig. 5a shows the six English sentences and their corresponding Chinese sentences used in this study. Firstly, Hong, Zhang and Liu Wrote each of the 12 sentences on the cylindrical microstructure TENG based smart self-powered

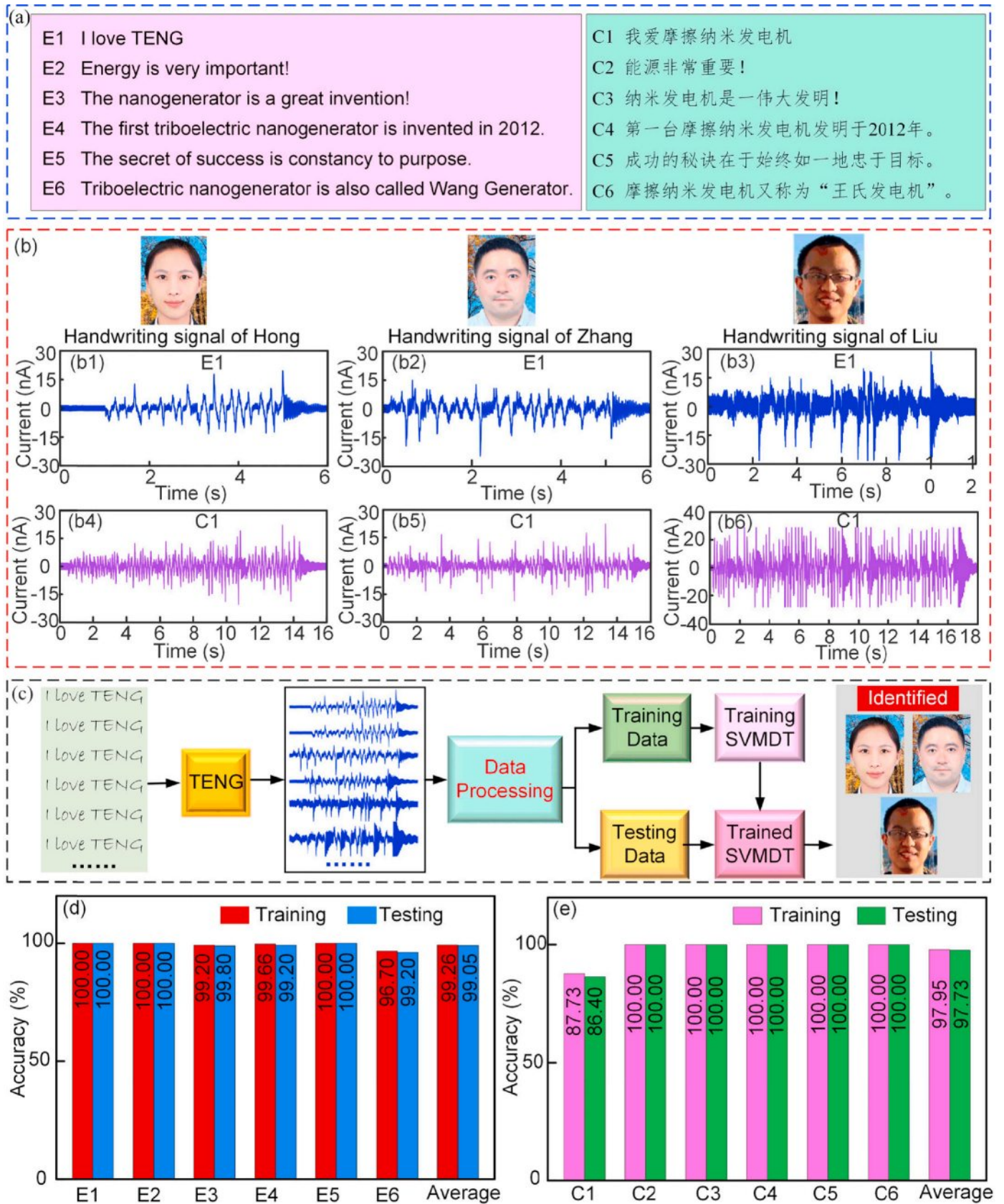


Fig. 5. The diagram of the TENG's application in sentences handwriting identification. (a) English sentences and the corresponding Chinese sentences for recognition. (b) The time-domain signal of Hong, Zhang and Liu wrote E1 and C1. (c) The flow charts of sentences handwriting recognition that combining TENG with the machine learning method. (d) The classification accuracies of the six English sentences. (e) The classification accuracies of the corresponding Chinese sentences.

handwriting pad 25 times and the handwriting signals were recorded. Fig. 5b gives their handwriting signals of E1 and C1 and it was seen that their handwriting signal exhibited large differences in time-domain (The movie S1–S3 show the real-time handwriting signals of Hong, Zhang and Liu). Also, large differences could be found in the frequency domain signal, as shown in Fig. S8. The signal processing procedure and machine learning methods for sentences handwriting recognition was the same as that used in words handwriting recognition. Fig. 5c exhibits the identification flow chart of the 12 sentences. Handwriting signal of sentences acquired by using the cylindrical microstructure TENG and then processed, divided into training data and testing data. The SVM-DT was trained by using training data and then testing data was put in the trained SVM-DT, thus the handwriting signal of Hong, Zhang and Liu were identified. Fig. 5d and e shows the classification accuracies and very high average classification accuracies that 99.05% and 97.73% were obtained for English sentences and Chinese sentences, respectively. It was worth noting that some of the above sentences including Arabic numerals and different punctuation which are more in line with daily practical applications. Hence, we believe that the TENG is nearly perfect in human handwriting signal recording and it could be a killer in handwriting identification.

4. Conclusion

In summary, we have developed two kinds of textured TENGs, and their applications in personal handwriting signature recognition were presented. The BPO leaf-inspired TENG exhibited the highest performance under a normal load of 5 N which is close to the human writing force. The well-proportioned concave-convex micro/nano-structure of BPO leaf enlarged the contact area and enhanced the output performance of TENG. BPO leaf-inspired and cylindrical microstructure based TENG was used as a smart self-powered handwriting pad for sensing comprehensive handwriting information of different people. The English words, Chinese characters, Arabic numerals were written and the handwriting signals were recorded by the BPO leaf-inspired TENG. The handwriting signals of six English sentences and the corresponding Chinese sentences measured by cylindrical microstructure based TENG. The results showed that obvious unique features exhibited in the handwriting signals recorded by TENG. Advanced signal and data processing methods were used to extract key feature information and reduce the data dimension. Then combined with an SVM-DT multi-class classifier, the handwriting signatures could be recognized and the classification accuracies of 99.66%, 93.63%, 91.36%, 99.05% and 97.73% were obtained for English words, Arabic numerals, Chinese characters, English sentences and the corresponding Chinese sentences, respectively. The designed textured TENG worked as a smart handwriting pad and exhibited robust performance for sensing six individuals' handwriting. The results strongly suggested that the textured TENG exhibited great potential in personal handwriting signature identification, security defense and private information protection applications.

CRediT authorship contribution statement

Weiqiang Zhang: Conceptualization, Methodology, Formal analysis, Software, Writing - original draft, Investigation, Data curation. **Linfeng Deng:** Software, Formal analysis, Investigation, Validation, Data curation, Funding acquisition. **Lei Yang:** Formal analysis, Investigation, Funding acquisition. **Ping Yang:** Formal analysis, Data curation. **Dongfeng Diao:** Formal analysis, Funding acquisition, Investigation, Supervision. **Pengfei Wang:** Methodology, Formal analysis, Investigation. **Zhong Lin Wang:** Formal analysis, Methodology, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no competing interests.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.nanoen.2020.105174>.

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