Advanced Robotics

ISSN: 0169-1864 (Print) 1568-5535 (Online) Journal homepage: http://www.tandfonline.com/loi/tadr20

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To cite this article: Ling Li, Shuo Jiang, Peter B. Shull & Guoying Gu (2018): SkinGest: artificial skin for gesture recognition via filmy stretchable strain sensors, Advanced Robotics, DOI: 10.1080/01691864.2018.1490666

To link to this article: https://doi.org/10.1080/01691864.2018.1490666

Published online: 03 Jul 2018.

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ADVANCED ROBOTICS
https://doi.org/10.1080/01691864.2018.1490666

FULL PAPER

SkinGest: artificial skin for gesture recognition via filmy stretchable strain sensors*

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ABSTRACT
Stretchable sensors are promising in the field of wearable robotics. To date, it is still a challenge to design an artificial skin with thin and sensitive stretchable sensors. In this paper, we present a new artificial skin, SkinGest, integrating filmy stretchable strain sensors and machine learning algorithms for gesture recognition of human hands. The presented sensor has a sandwich structure consisting of two elastomer layers on the outside and one soft electrode layer in the middle. Based on the improved fabrication process, we make the sensor's thickness down to 150 µm, while keeping the gauge factor (GF) up to 8. Then, we integrate the machine learning algorithms (using LDA, KNN and SVM classifiers) with the stretchable sensors in our SkinGest system for gesture recognition. Supported by the experimental data from different subjects, our SkinGest system succeeds in identifying American sign language 0–9 with an average accuracy of 98%. The results demonstrate that the proposed SkinGest system provides a promising platform for future potential virtual reality and sign language recognition applications.

ARTICLE HISTORY
Received 28 November 2017
Revised 17 March 2018, 22 May 2018, and 27 May 2018
Accepted 11 June 2018

KEYWORDS
Stretchable sensors; soft materials; artificial skin; gesture recognition

1. Introduction

Gesture recognition is an intuitive way for humans to interact with intelligent machines and is increasingly important in virtual reality. However, the primary way for humans to interact with intelligent devices is still via keyboards or hand-held equipment. More intuitively, accurate and comfortable wearable devices are promising in daily life [1].

To this end, various band-like wearable devices with the traditional rigid sensors have been developed for gesture recognition [2]. For instance, Guo et al. explored Electromyography (EMG) combined band-like wearable device to recognize amputees' intention for a prosthetic hand [3]. Jiang et al. utilized a wristband fusing the EMG and inertial measurement sensors for hand gesture recognition [4]. Dementyev et al. used an array of force resistive sensors around the wrist to detect tendon movements [5]. Jung et al. employed an air bladder with pressure sensors around the forearm to detect muscular activity [6]. These approaches are accurate for a limited set of hand gestures, but classification accuracy generally decreases when the number of gestures increases. Data gloves offer another approach to recognize and reconstruct finger movement with high accuracy [7,8]. However, they are typically large, bulky and expensive.

Therefore, developing a kind of light weight, cheap sensors for gesture recognition is of great significance [9–13]. As shown in Figure 1, many interesting works have been reported to develop sensing skins with soft sensors. Kyongkwan et al. developed a sensing skin to measure abduction and adduction of fingers [14], which was bulky. To make the sensing skin thinner and lighter, commercial elastomer VHB (3M, thickness = 0.5 mm) and conductive bond could be applied to fabricate a transparent and extremely thin artificial skin shown in Figure 1(b) [15]. However, VHB has strong viscosity and may influence the comfortableness, thus human-friendly silicone gel becomes a better choice [16]. Muth et al. reported an embedded 3D-printing method for fabricating strain sensors within highly conformal and extensible elastomeric matrices Ecoflex [17]. Frank et al. designed an array of modular liquid metal-embedded silicone elastomer sensors to measure hand motion and contact pressure [18]. In [19], a wearable soft artificial skin applying liquid metal and elastomer Ecoflex was developed to measure the motions of the metacarpophalangeal point

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*This paper is an extension of 'Fabrication and Testing of a Filmy "Feelingless" Stretchable Strain Sensor' on 2017 IEEE/SICE International Symposium on System Integration.
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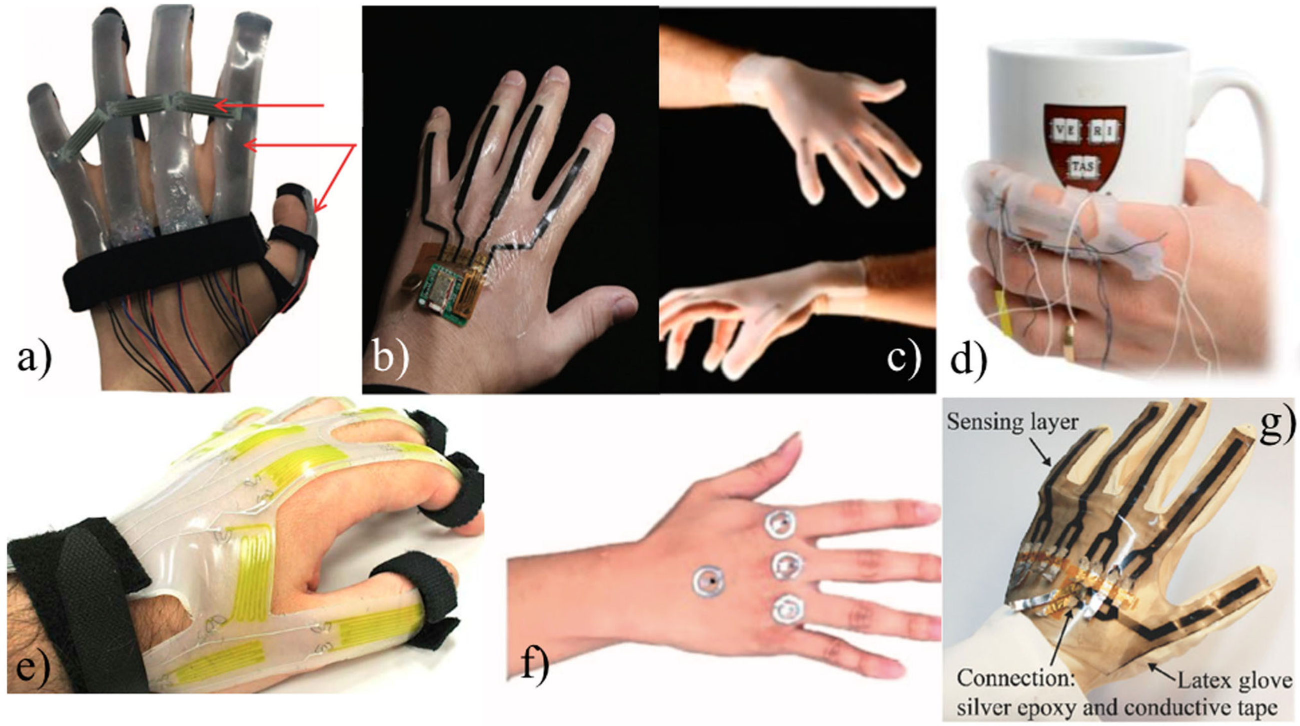

Figure 1. Previously developed gesture recognition systems. (a) A wearable soft sensor for measuring the flexion/extension of each finger and the abduction/adduction between fingers [14]; (b) a sensing skin manufactured by applying soft transfer printing technique [15]; (c) a 3D-printed glove-like sensor to identify gestures [17]; (d) a modular soft sensor-embedded glove to detect finger motion and tactile pressure [18]; (e) a wearable soft artificial skin applying liquid metal [19]; (f) a skin-attachable stretchable sensor based on liquid metal on finger joints to monitor motions [20]; (g) a capacitive type sensing glove with high stretchability and great linearity [21].

(MCP) and the proximal interphalangeal point (PIP) joints of each finger as well as the motion between thumb and index fingers. Jeong et al. introduced a liquid metal-integrated system for human motion sensing, combining soft materials and advanced near-field-communication functionality [20]. Although liquid metal is one of the most popular electrodes, some works have been conducted in developing other replaceable electrodes. Shintake et al. developed a capacitive-type sensing glove with high stretchability and great linearity, using carbon-filled elastomer as electrode and Ecoflex as substrate. Applying film-casting technique and laser ablation, the sensors could be fabricated rapidly (Figure 1(g)) [21]. Seok et al. demonstrated a high-performance wearable strain sensor using heterostructure nanocrystal solids with high accuracy and thin thickness [22].

Although previous works have demonstrated the great feasibility of applying soft sensors in gesture detecting, more requirements come to develop an ideal soft sensor with features like invisible and easy to be attached to the skin [23,24]. In general, the reported works usually failed to simultaneously achieve these two objectives, limited by the materials and fabrication process. An ideal artificial skin also asks for other features like thin thickness, light weight and extreme stretchability. Recently, various manufacturing methods have been developed in order to achieve these features [25–30]. Among all these methods, one of the most common ways is to cure soft elastomer and then embed conductive materials upon it [15,31]. Channels are implemented into the elastomer base and then conductive materials are injected [19]. However, the deficiency of this manufacturing method is that certain thickness of elastomer base is required to create channels, limiting the whole thickness of sensors to be thinner [32,33]. Thus, the whole weight of the sensor is difficult to decrease as well. In addition, the manufacturing process is relatively complex [14]. Besides, few works have discussed the universal practicability of their artificial skins though experimental data from different subjects.

In this paper, we present a new artificial skin, SkinGest, integrating filmy stretchable strain sensors (Figure 2(a)) and machine learning algorithm for gesture recognition of human hands (Figure 2(b)). The presented sensor has a sandwich structure consisting of two elastomer layers on the outside and one soft electrode layer in the middle. Based on the improved fabrication process, we make the sensor's thickness down to 150 μm, which is about 47% ∼ 90% thinner than the reported works. At the same time, the gauge factor (GF) of our developed sensing system is up to 8, higher than the available works

Figure 2. (a) Structure of a single sensor; (b) SkinGest prototype for gesture recognition.

with the silicone and carbon grease as well. Furthermore, machine learning algorithms, using LDA, KNN and SVM classifiers, are integrated into our SkinGest system for gesture recognition and sign language digits identification. Finally, we conduct the experiments using our SkinGest system by different subjects. Experimental results demonstrate that our artificial skin system succeeds in identifying American sign language (ASL) 0–9 with an average accuracy of 98%.

The rest of this paper is organized as follows. The fabrication process is introduced in Section 2. Section 3 presents the performance of our sensor, as well as its application in gesture recognition with experimental data from different subjects. Finally, the conclusion of this study is drawn in Section 4.

2. Fabrication

The fabrication part involves multiple steps, including polymer casting, electrode embedment and sealing [34]. Figure 3 shows the schematic description of the whole manufacturing process. Elastomer is chosen as the substrate because of its stretchability and transparency. Carbon grease is employed as the stretchable electrode owing to its moderate mobility, and flexible copper–tin fabric wires are adopted for connections between sensors and electronics for its outstanding flexibility as well as acceptable electrical conductivity [35].

2.1. Polymer casting

The base layer and the sealing layer of this sensor are made of soft elastomer (Sylgard, 184 or 186 silicone elastomer) by mixing two parts (resin and hardner, 10:1 mixed ratio in weight). To fabricate the thin films, an automatic film applicator coater (Zehnther, ZAA 2300, with a drawing speed of 0–99 mm/s and a resolution of 1 μm) is applied (see Figure 3(a)). The distance between the wire-bar applicator and the automatic film applicator coater platform is able to be adjusted to get films with customized thickness. The detailed processes for fabrication are listed as follows, which can also be seen in Figure 3.

- Firstly, a polyethylene terephthalate (PET) film is placed on the coating machine platform as a substrate layer (Figure 3(a)).
- Secondly, a sacrificial layer (polyacrylic acid and isopropyl alcohol, 1:4 mixed in weight) with a thickness of 20 μm is coated with a drawing speed of 3 mm/s. Then, the film is cured at room temperature for approximately 5 min (Figure 3(b)). By using the sacrificial layer, the PET film and elastomer layer can be separated easily owing to its volatility.
- Thirdly, an elastomer layer is coated upon the sacrificial layer with a drawing speed of 1 mm/s, then cured at 60°C for approximately 25 min (Figure 3(c)).
- Fourthly, the whole three layers, including the PET layer, the sacrificial layer and the elastomer layer, are transferred into a sink with hot water inside for 3 min.

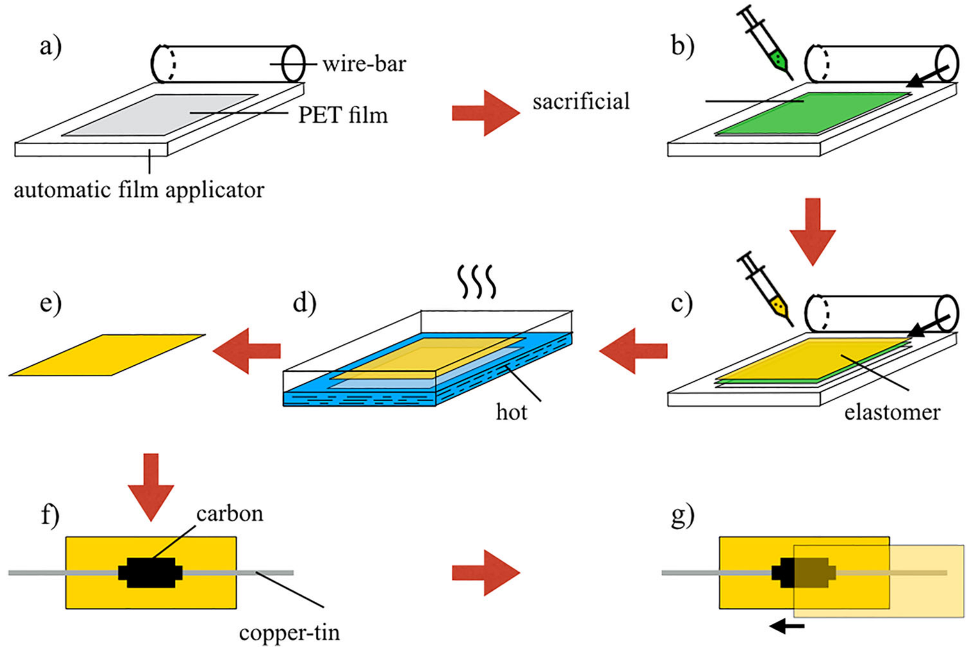

Figure 3. The manufacturing process of a filmy strain sensor: (a) a PET film is placed on the coating machine; (b) a sacrificial layer is coated and cured upon the PET film; (c) an extremely soft elastomer layer is coated and cured upon the sacrificial layer; (d) these three layers are transferred into a sink with hot water inside to dissolve the sacrificial layer; (e) the extremely soft elastomer is taken off; (f) carbon grease and cooper-tin fabric wires are embedded; (g) another layer of extremely soft elastomer is coated to seal.

The sacrificial layer can be dissolved into water, and then the elastomer film can be taken off easily (Figure 3(d)). Alternatively, the layers can be placed at room temperature for about 12 h and the sacrificial layer will volatilize to separate the PET and the elastomer layers. Applying these four steps, the elastomer films can be produced in large quantities (Figure 3(e)).

2.2. Electrode embedment

The elastomer films are cut into specific shapes. Here the shape of the electrode is designed as a rectangle with a length of 20 mm and a width of 10 mm. Carbon conductive grease (847, MG Chemicals), which is applied as the resistor electrode, is brushed into the rectangle with extremely thin thickness. Through an LCR meter, the resistance values of the sensor are observed, and thus the amount of carbon grease can be controlled and adjusted depending on requirements. Cooper–tin fabric is then used as the conductive wires to connect the resistor electrode with the LCR meter (Figure 3(f)).

2.3. Sealing

Beyond the electrode area above the elastomer film, an extreme thin layer of elastomer 184 or 186 is brushed as the adhesive. Another elastomer film with the same thickness is coated above before the thin layer solidifies. Then, the sealed sample is cured at 60°C for approximately 25 min again (Figure 3(g)). The completed strain sensors have thin thickness and light weight mainly depending on the thickness of the elastomer layer, which can be user-defined. Areas beyond the electrode are transparent.

3. Experiments

3.1. Performance

Since the fabrication method is also appropriate for other kinds of elastomers, a group of experiments is performed to decide the most suitable material. In this section, we apply this method to fabricate three kinds of elastomer films that are commonly used to fabricate soft sensors, Ecoflex 30 (Smooth-On), 184 and 186 silicone elastomer (Sylgard). Another sandwich-structured sensor with a substrate made from commercial material VHB (4905, 3M, thickness = 0.5 mm), which is often used to make filmy soft sensors at present, is manufactured as a comparison. After the fabrication process, the sensor samples are stretched to test resistance responses with deformation during loops. The sensitivity of the strain sensor can be obtained in the following equation:

$$\Delta R/R = G\varepsilon + \alpha\theta, \tag{1}$$

where ΔR stands for the resistance change and R is the original resistance, G, ε, α, θ mean the GF, the strain

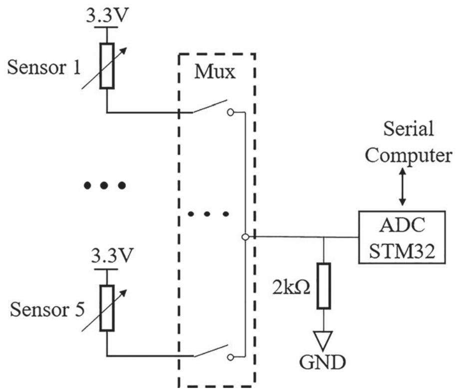

Figure 4. The schematic diagram of the test circuit.

applied, the temperature coefficient and the temperature change, respectively.

With an additional thin layer of silicone gel, the sensor is easily adhered to the human skin. Owing to the excellent stretchability of soft elastomer and carbon grease, the sensor can be used to detect large deformations of the human body like the motions of finger joints, wrist joints and elbow joints. Different gestures cause different stretch compositions among fingers, resulting in different resistance change patterns. Therefore, by measuring the resistance of sensors, gestures can be reconstructed by a proper algorithm. A resistance measuring circuit is designed with 5-channel sensors connected to a voltage divider circuit via a multiplexer (CD74HC4067, Texas Instruments, USA) (Figure 4). A standard resistance is chosen to share the voltage provided by a microprocessor (STM 32 F429, STMicroelectronics, Italy). The inner analog to digital converter (ADC) samples the analog voltage between sensors and standard resistance. Digitalized voltage values are transmitted to the computer via I2C communication protocol and MATLAB is used to process all of the data on a standard desktop computer with a sampling frequency of 20 Hz.

Figure 5(a) plots the relationship between strain and response for the sensor samples with different substrates. In this test, the length of the electrode is loaded towards a deformation of 100% and then unloaded to the original state. From Figure 5(a), the responses of sensors during strain loops can be observed. Sample with VHB as the substrate shows nonlinear behavior while the other three show approximate linearity. However, it is notable that the maximum resistances of sensors inevitably increase during loops, which is undesirable for the soft sensors. Among them, the one made from VHB substrate is the most prominent one while the one made from 186 elastomer substrate shows less variation and best repeatability. Sensors made from 184 elastomer and Ecoflex 30 substrates also demonstrate linearity and repeatability over the sensor fabricated from commercial VHB substrate.

With the material elastomer 186, another group of experiments is conducted to identify the influence of membrane thickness of the sensors. Experimental results demonstrate that the responses of our developed sensors are approximately linear and the sensitivity (GF) increases as the thickness decreases (Figure 5(b)).

Another experiment is conducted to investigate the temperature effect on sensing performance. From the experimental results, we can see that under a certain temperature, the sensor is robust over time (Figure 5(c)). With the increase in temperature, the performance of the sensor slightly changes ($\Delta R/R < 0.005$ under 40°C). Therefore, the temperature effect can be ignored under 40°C. In this sense, Equation (1) can be simplified as

$$\Delta R/R = G\varepsilon. \tag{2}$$

Furthermore, in this paper, we integrate multiple single strain sensors into an artificial skin, SkinGest, to recognize hand gesture (Figure 6).

An integrated sensor system with five single strain sensors on a palm-like elastomer film is fabricated applying the process in Section 2. The integrated artificial skin is used to detect the motions of MCP joints except for the thumb finger. The DIP joint instead of MCP joint of thumb finger is measured because it has more obvious motion. The integrated artificial skin has a total weight of about 4 g with an area of 160 cm^2, resulting in a pressure of 0.25 Pa towards the back of the hand (a piece of A4 paper weighs 4.5 g with an area of 624 cm^2, leading to a pressure of 0.072 Pa).

3.2. Gesture recognition

A serial of different gestures are designed and performed, and machine learning algorithms are used to classify these gestures. The voltage value data collected from the sensor is transformed to sensor resistance as a feature because the resistance has a relatively linear relationship with sensor's stretching, which is directly correlated to finger's movement. Linear discriminant analysis (LDA), K nearest neighbor (KNN) and support vector machine (SVM), are employed. Because of the linearity of the measured signal, a linear kernel is chosen for SVM. All the algorithms are run on MATLAB on computers and open source of LIBSVM [36] is used for SVM.

Preliminary testing is conducted with six subjects (three males and three females: 24.0 ± 1.1 years, height: 168.0 ± 13.4 cm, weight: 60.2 ± 14.8 kg). As a consideration that target gestures should be intuitive and commonly used in daily life, digits 0–9 from ASL are chosen as the target gesture sets which are often used [36,37]

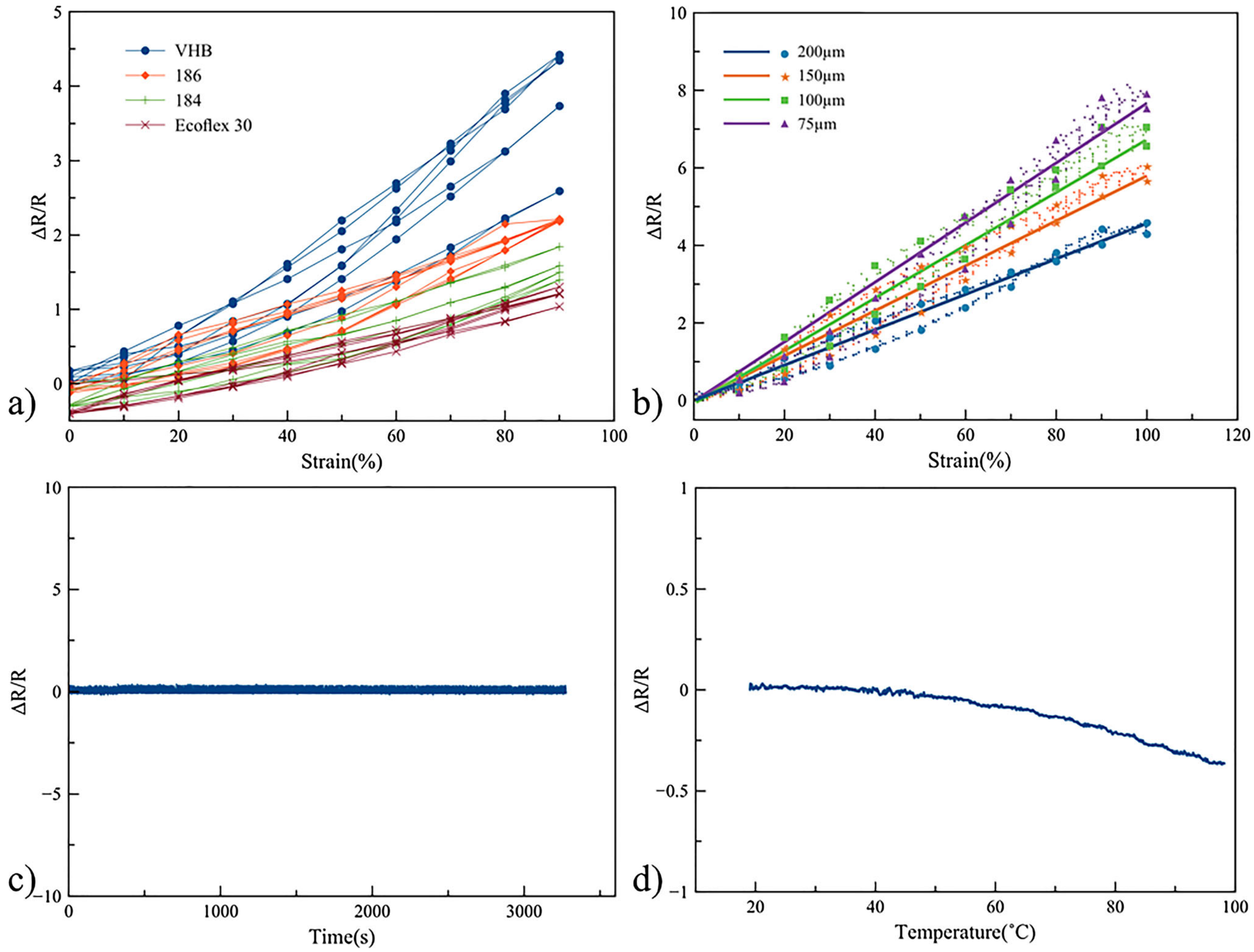

Figure 5. The influence on sensing performance caused by materials (a) and substrate thickness (b), and the change in sensor's resistance along with time (c) and temperature (d).

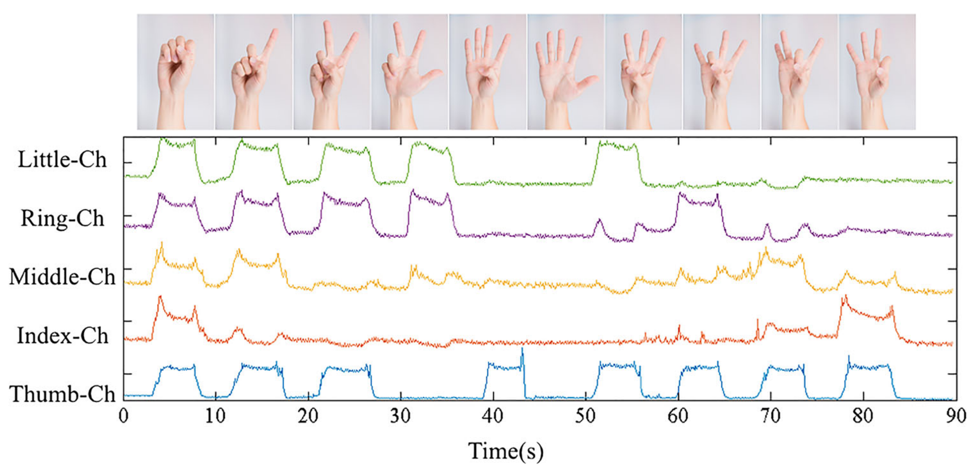

Figure 6. Raw signals of SkinGest system in performing American sign language digits 0～9.

in human computer interaction research. Sensors are put on subject's hand via user friendly gel. Subjects are instructed to do corresponding gestures for 10 trials. Each gesture is performed for 5 s per trial and the sampling rate is 20 Hz since normal hand movement frequency is generally low than 5 Hz [38]. The changes in resistance values of all five strain sensors are observed in real time through MATLAB when different gestures

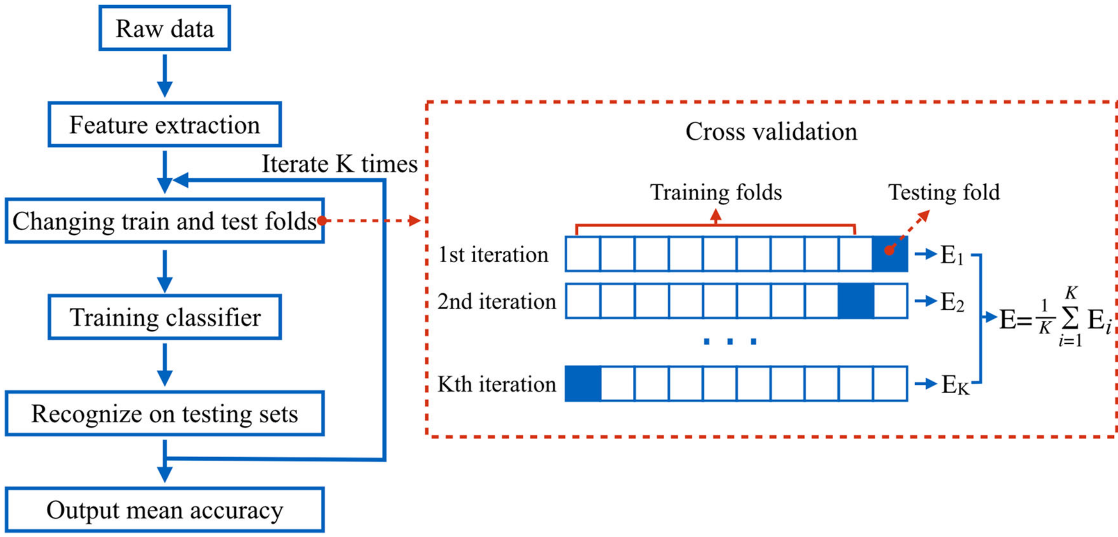

Figure 7. Flow chart for recognition algorithm.

are performed. The resistance value of each sensor grows up obviously when the corresponding finger bends. Even though noise exists, the differences between different gestures are remarkable (see Figure 6). Signals from bottom to top come from sensors placed on thumb, index, middle, ring and little fingers, respectively.

Offline methods are used to access classification accuracy. Leave-one-out cross validation (LOOCV) [5,39] is commonly used to access the performance of classification tasks. LOOCV method uses 1 subset as testing and the others as training and iterates the same procedure so that every subset has been chosen as testing sets once. Accuracy is calculated as the mean of K (K equals to total numbers of subsets) times predictive accuracy (Figure 7). $97.8 \pm 2.3\%$, $97.9 \pm 1.7\%$, $97.9 \pm 1.7\%$ accuracies are obtained for the LDA, KNN and SVM classifiers, respectively (Figure 8).

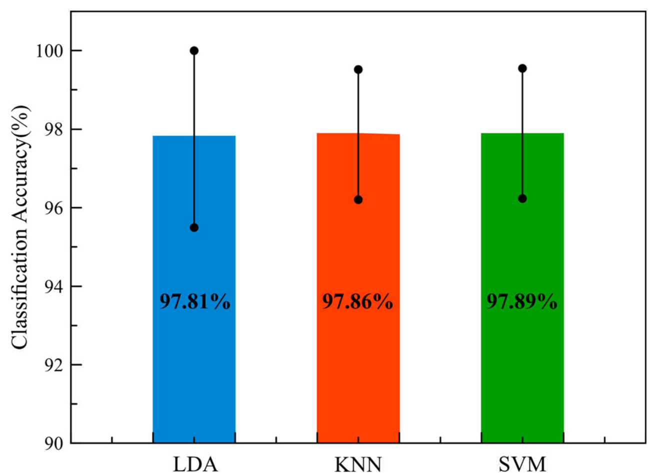

Figure 8. Classification accuracy of different classifiers. LDA: linear discriminant analysis; KNN: K nearest neighbor; SVM: support vector machine.

3.3. Discussion

Here, we compare several features of our artificial skin with the current available soft artificial skins in reported works including the materials, sensitivity, thickness and stretchability (Table 1).

Morphological experiments are conducted to identify the influences of different substrate materials and thicknesses on the performance of the sensors. To this end, elastomer 184, 186, Ecoflex and VHB are applied as the substrate for comparison, respectively. The experimental results indicate that the sensor with the elastomer 186 shows the best performance. Furthermore, sensors with substrate thicknesses of 200, 150, 100 and 75 μm are compared and results demonstrate that the sensitivity of the sensor increases with the decrease of the morphological thickness. We also demonstrated in Table 1 that the thickness of our sensor is reduced by 47–90% compared with other works while the sensitivity increases greatly up to 8.

With respect to the classification accuracy of gesture recognition, results are also compared with forearm and wrist based ways [3,5], because in this work, sensors are put on finger joints while band-like solutions measure indirect signals such as wrist shape change or muscle electrical signals. Concerning the wearable comfort, the proposed system is highly soft and stretchable and compliant to shape change with finger flexion without exerting too much interference. Besides, the sensors only cover the back area of the hand and thus do not influence the palm and finger sensation. Although the sensors are attached to the skin by gel, it is easy to be detached and can be reused for multiple times.

Table 1. Comparisons of features of the current available soft artificial skins.

Reference	Elastomer material	Electrode material	Sensitivity (GF)	Thickness (µm)	Stretchability
[14]	Silicone	EGaIn	3.21	2000	35%
[15]	VHB 4905, 3M	Conducting bond (eCAP 7850, 3M)	0.6	800–1800	100%
[17]	Ecoflex	Conductive ink	5	1000	400%
[18]	Ecoflex	Liquid metal	4.23	2000	30%
[19]	Ecoflex	Liquid metal	1.667	2000	200%
[20]	PDMS	Liquid metal	2	380	50%
[21]	Ecoflex	Carbon black-filled elastomer	0.83–3.37	940	500%
Our work	PDMS	Carbon grease	8	150	100%

However, the results still suffer from some misclassification, for which the reason lies in some noise interference and hysteresis characteristics of sensors. Besides, not all subjects can do standard target gestures. For example, subject 1 can not only bend middle finger without moving ring finger, thus making gesture digit 8 not standard.

4. Conclusion

In this paper, we present an improved manufacturing process to fabricate a firmly stretchable strain sensor. The developed sensor is of resistance type and composed of three layers, two sealing layers and an electrode layer in-between. Soft elastomer is used as the sealing layer while carbon conductive grease is applied as the resistance electrode, copper–tin fabric as the conductive wires. Sensors manufactured in this way have noteworthy features, such as thin thickness, light weight, easy fabricated method, low cost and high transparence. For the sake of improving sensitivity and stability, comparative experiments on different substrate materials and sensor's thickness are conducted. Finally, the thickness of our sensor is reduced down to 150 µm while the GF is increased up to 8.

This study also presents the validation of artificial skin system to recognize precise finger gestures. As a concern that breathability may have an influence on comfortableness, ventilation holes are designed on the artificial skin. Experimental data from six subjects demonstrate that the SkinGest system has a high average accuracy of 98% for gesture recognition and sign language digits identifying.

Although sensors fabricated in this technology present excellent feasibility, we find that the characteristics change as the number of use increases during experiments. Besides, experimental results demonstrate that substrates made from different kinds of elastomers will affect the performance, which may be caused from the interaction between substrate and electrode, still needing more study to investigate. In order to fabricate a complete invisible wearable sensor, which asks for total transparence and extremely light weight, we are also exploring some other conductive materials as alternative electrodes and refining the manufacturing process.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by National Natural Science Foundation of China [grant number 51622506], and in part by Science and Technology Commission of Shanghai Municipality [grant number 16JC1401000].

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References

[1] Li H, Yang W, Wang J, et al. Wifinger: talk to your smart devices with finger-grained gesture. Proceedings of the 2016 ACM international joint conference on pervasive and ubiquitous computing. New York: ACM; 2016. p. 250–261.

[2] Poh MZ, Swenson NC, Picard RW. A wearable sensor for unobtrusive, long-term assessment of electrodermal activity. IEEE Trans Biomed Eng. 2010;57(5): 1243–1252.

[3] Guo W, Sheng X, Liu H, et al. Development of a multichannel compact-size wireless hybrid sEMG/NIRS sensor system for prosthetic manipulation. IEEE Sens J. 2016;16(2):447–456.

[4] Jiang S, Lv B, Guo W, et al. Feasibility of wrist-worn, real-time hand and surface gesture recognition via sEMG and IMU sensing. IEEE Trans Ind Inf. 2017:1. doi:10.1109/TII.2017.2779814.

[5] Dementyev A, Paradiso JA. Wristflex: low-power gesture input with wrist-worn pressure sensors. Proceedings of the 27th annual ACM symposium on user interface software and technology. New York: ACM; 2014. p. 161–166.

[6] Jung PG, Lim G, Kim S, et al. A wearable gesture recognition device for detecting muscular activities based on air-pressure sensors. IEEE Trans Ind Inf. 2015;11(2):485–494.

[7] Falcao C, Lemos AC, Soares M. Evaluation of natural user interface: a usability study based on the leap motion device. Procedia Manuf. 2015;3:5490–5495.

[8] da Silva AF, Goncalves AF, Mendes PM, et al. FBG sensing glove for monitoring hand posture. IEEE Sens J. 2011;11(10):2442–2448.

[9] Yu KJ, Yan Z, Han M, et al. Inorganic semiconducting materials for flexible and stretchable electronics. npj Flex Electron. 2017;1(1):638.

[10] Ma Y, Liu N, Li L, et al. A highly flexible and sensitive piezoresistive sensor based on mxene with greatly changed interlayer distances. Nat Commun. 2017;8(1):4248.

[11] Liu Y, Pharr M, Salvatore GA. Lab-on-skin: a review of flexible and stretchable electronics for wearable health monitoring. ACS Nano. 2017;11(10):9614–9635.

[12] Yeo JC, Lim CT, et al. Emerging flexible and wearable physical sensing platforms for healthcare and biomedical applications. Microsyst Nanoeng. 2016;2:16043.

[13] Lin B, Recke B, Knudsen JK, et al. A systematic approach for soft sensor development. Comput Chem Eng. 2007;31(5):419–425.

[14] Ro K, Kim S, Park W, et al. Development of a wearable soft sensor system for measuring finger motions. 2016 16th international conference on control, automation and systems (ICCAS), HICO, Gyeongju, Korea. IEEE; 2016. p. 549–554.

[15] Bartlett MD, Markvicka EJ, Majidi C. Rapid fabrication of soft, multilayered electronics for wearable biomonitoring. Adv Funct Mater. 2016;26(46):8496–8504.

[16] Gu GY, Zhu J, Zhu LM, et al. A survey on dielectric elastomer actuators for soft robots. Bioinspir Biomim. 2017;12(1):011003.

[17] Xu Y, Wu X, Guo X, et al. The boom in 3d-printed sensor technology. Sens. 2017;17(5):1166.

[18] Hammond FL, Menguc Y, Wood RJ. Toward a modular soft sensor-embedded glove for human hand motion and tactile pressure measurement. 2014 IEEE/RSJ international conference on intelligent robots and systems (IROS 2014); Chicago, IL. IEEE; 2014. p. 4000–4007.

[19] Chossat JB, Tao Y, Duchaine V, et al. Wearable soft artificial skin for hand motion detection with embedded microfluidic strain sensing. 2015 IEEE international conference on robotics and automation (ICRA); Seattle, Washington. IEEE; 2015. p. 2568–2573.

[20] Jeong YR, Kim J, Xie Z, et al. A skin-attachable, stretchable integrated system based on liquid gainsn for wireless human motion monitoring with multi-site sensing capabilities. NPG Asia Mater. 2017;9(10):e443.

[21] Shintake J, Piskarev E, Jeong S H, et al. Ultrastretchable strain sensors using carbon black-filled elastomer composites and comparison of capacitive versus resistive sensors. Adv Mater Technol. 2018;3(3):1700284.

[22] Lee WS, Lee SW, Joh H, et al. Designing metallic and insulating nanocrystal heterostructures to fabricate highly sensitive and solution processed strain gauges for wearable sensors. Small. 2017;13(47). doi:10.1002/smll.201702534

[23] Ho MD, Ling Y, Yap LW, et al. Percolating network of ultrathin gold nanowires and silver nanowires toward 'invisible' wearable sensors for detecting emotional expression and apexcardiogram. Adv Funct Mater. 2017;27(25):1700845.

[24] Drotlef DM, Amjadi M, Yunusa M, et al. Bioinspired composite microfibers for skin adhesion and signal amplification of wearable sensors. Adv Mater. 2017;29(28). doi:10.1002/adma.201701353.

[25] Do TN, Visell Y. Stretchable, twisted conductive microtubules for wearable computing, robotics, electronics, and healthcare. Sci Rep. 2017;7(1):1753.

[26] Fujiwara K, Kano M, Hasebe S, et al. Soft-sensor development using correlation-based just-in-time modeling. AIChE J. 2009;55(7):1754–1765.

[27] Pantelopoulos A, Bourbakis NG. A survey on wearable sensor-based systems for health monitoring and prognosis. IEEE Trans Syst Man Cybern C (Appl Rev). 2010;40(1):1–12.

[28] Lee H, Kwon D, Cho H, et al. Soft nanocomposite based multi-point, multi-directional strain mapping sensor using anisotropic electrical impedance tomography. Sci Rep. 2017;7:39837.

[29] Zhou Y, He J, Wang H, et al. Highly sensitive, self-powered and wearable electronic skin based on pressure-sensitive nanofiber woven fabric sensor. Sci Rep. 2017;7(1):950.

[30] Araromi O, Poulin A, Rosset S, et al. Optimization of thin-film highly-compliant elastomer sensors for contractility measurement of muscle cells. Extreme Mech Lett. 2016;9:1–10.
[31] Polygerinos P, Wang Z, Galloway KC, et al. Soft robotic glove for combined assistance and at-home rehabilitation. Rob Auton Syst. 2015;73:135–143.
[32] Chossat JB, Shin HS, Park YL, et al. Soft tactile skin using an embedded ionic liquid and tomographic imaging. J Mech Robot. 2015;7(2):021008.
[33] Chossat JB, Park YL, Wood RJ, et al. A soft strain sensor based on ionic and metal liquids. IEEE Sens J. 2013;13(9):3405–3414.
[34] Li L, Jiang S, Tao Y, et al. Fabrication and testing of a filmy feelingless stretchable strain sensor. 2017 IEEE/SICE international symposium on system integration (SII); Taipei, China. IEEE; 2017. p. 362–367.
[35] Tao YD, Gu GY. Design of a soft pneumatic actuator finger with self-strain sensing. International conference on intelligent robotics and applications; Springer; 2017. p. 140–150 .
[36] Chang CC, Lin CJ. Libsvm: a library for support vector machines. ACM Trans Intell Syst Technol. 2011;2(3):27.
[37] Lin JW, Wang C, Huang YY, et al. Backhand: sensing hand gestures via back of the hand. Proceedings of the 28th annual ACM symposium on user interface software & technology. New York: ACM; 2015. p. 557–564.
[38] Kuboyama N, Nabetani T, Shibuya K, et al. Relationship between cerebral activity and movement frequency of maximal finger tapping. J Physiol Anthropol Appl Human Sci. 2005;24(3):201–208.
[39] McIntosh J, McNeill C, Fraser M, et al. Empress: practical hand gesture classification with wrist-mounted EMG and pressure sensing. Proceedings of the 2016 CHI conference on human factors in computing systems. New York: ACM; 2016. p. 2332–2342.