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Electronic Supplementary Information

Screen Printing of Stretchable Silver Nanomaterial Inks for Stable Muscle-machine Controlling

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1. Experimental Section

Materials: Ag flakes (product number: 327077 Aldrich, Ag flakes, 10 μm, >99.9% trace metals basis) were purchased from Sigma Aldrich. Ag inks (containing 80 wt% Ag nanoparticles) were purchased from Shenzhen Elechem Technology LTD. Lipoic acid (LA, 99%) and tannic acid (TA, 98%) were obtained by Shanghai Aladdin Biochemical Technology Co.

Preparation of the silver nanomaterial: The silver nanomaterial was prepared by simple blending. Ag flakes (4 g) and commercial Ag inks (1.25 g) were blended in ethylene diacetate (1.3 ml) with a speed of ~500 rpm/min for 10 min at room temperature.

Preparation of the PLTA adhesive film: The PLTA polymer was prepared through ring-opening polymerization. LA (5 g) monomer was added to a round-bottom flask and heated at 70 °C until the monomer melted. Then, adding absolute methanol (20 ml) with a agitating speed of ~3000 rpm/min until the monomer was completely dissolved. The yellowish solution was obtained. And then, another monomer TA (2g, 40 wt%) dissolved in methanol before was added drop by drop. After stirring for 10 min, the PLTA polymer solution was obtained. Finally, the polymer solution was poured into a teflon mold and allowed to evaporate into a film at room temperature for 24 hours.

Preparation of different polymer substrates for screen printing: (1) SEBS substrate was prepared by SEBS H1062. SEBS H1062 (20 g) and toluene solvent (100 ml) were placed in a 200 ml bottle with blue mouth. Under the condition of 70 °C and 1000 rpm for 4 h, 200 mg/ml mixed solution was obtained. Pour 30 ml of the mixture into a glass petri dish (10 cm diameter). After standing for 24 h at room temperature to fully volatilize the solvent, we could obtain SEBS substrate. (2) Ecoflex substrate was prepared by the production “Ecoflex 0-30 PartA” and “Ecoflex 00-30 PartB” from Shanghai Smarttech Technology Co., Ltd.. The weight ratio of PartA and PartB was 1: 1. (3) PDMS was prepared by the production “SYLGARD 184 Silicone Elastomer Kit” from DOWSIL. The weight ratio was 10: 1. (4) TPU was purchased directly from Zhejiang Kangjia Plastic Products Co., Ltd..

The process of screen printing: About 2g Ag inks were used for screen printing under the room temperature (25 °C). Waiting for 5 minutes after printing, the printing substrate could be removed. Lastly, heating at 70 °C for 5 min to dry out the solvent.

Preparing process of conformal on-skin electrode arrays with three-layer structure: SEBS particles (20 g) was added into toluene solvent (100 ml) to obtain SEBS polymer solution (200 mg/ml). 20 ml solution was poured into a glass culture dish and left for 24 h to volatilize into film.The 3×3 electrode arrays (diameter of each circular electrode = 10 mm) were printed on the substrate SEBS by screen-printing. After heating at ~70 ℃ for ~5 min to dry out the electrodes, the PLTA adhesive layer was attached to the electrode arrays.

General Characterization: For the convenience of testing, Ag strips (80 mm × 10 mm) were printed on SEBS substrate. The contact angle between Ag layer and different polymer substrate was tested by Optical contact Angle tension tester (LSA/OSA-100/200/60). The adhesive strength between Ag layer and SEBS substrate was tested by a mechanical tester (M42, MTS Systems Corporation) at a speed of 5 mm/min. The surface topography of Ag strips (with 20 wt%, 40 wt%, 80 wt% of Ag flakes) at 0% strain and Ag strips (80 wt% of Ag flakes) at 20% stain, 80% strain, 150% strain were observed by a scanning electron microscope (SEM, SU8010, HITACHI, Japan). The interface impedance of the SEBS/Ag/PLTA electrodes (circle diameter = 20 mm) was tested by an electrochemical workstation (CH Instruments). The voltage was set at 220 mV at the ranges from 0.1 Hz to 1KHz. We adhered two electrodes on forearm skin with a central distance of 50 mm. For comparison, commercial electrodes (Junchen X-1 Ag/AgCl gel electrodes) were also tested under the same condition.

Mechanical Characterization: All mechanical properties were tested by a mechanical tester (M42, MTS Systems Corporation). For the measurement of the adhesion strength between PLTA and polymer substrates, cut the PDMS, SEBS, rubber and SEBS/Ag film into the shape of rectangle (70 mm × 20 mm) and stick to the glass slide. Cut the PLTA film into the shape of rectangle (20 mm × 20 mm) and stick to another glass slide. Adhered the PLTA film on the substrate and pulled them apart by MTS at 5 mm/min to record data. The PLTA film was cut into 80 mm × 10 mm strips and adhered to the forearm skin to test the adhesive energy. One end of the PLTA film was peeled from the skin at the angle of 180°, the speed of 5 mm/min. Stress-strain curves of 80 mm × 10 mm films were recorded through MTS at the speed of 1 mm/s.

Electrical Characterization: All electrical properties were recorded by a semiconductor parameter analyzer (Keithley 2636b). 80 mm × 10 mm Ag stripes were printed through screen-printing. Combining Keithley 2636b and MTS to measure the continuous resistance under the condition of stretching. The stretching speed was set at 1 mm/s to record the variation trend of resistance of Ag strips (0 wt%, 20 wt%, 40 wt%, 60 wt%, 80 wt%t, 100 wt% of Ag flakes) until the appearance of the sudden change. The resistance of Ag strips (80 wt% of Ag flakes) at 30% stain and 60% strain was recorded under the stretching cycles from 0 to 1000 while setting the speed of 1 mm/s.

EMG Monitoring: EMG signals were acquired by using a three-electrode system. Two of them were working electrodes by using our AWS electrodes, and one of them was the reference electrode by using a commercial electrode. To acquire ECG signals, AWS electrodes were placed on the chest of volunteers. Then, we connected the AWS electrodes with a LiKang PC-80A ECG monitor together by lead wire to amplify and collect ambulatory ECG signals. To minimize the noise generated by the movement, the cables were fixed onto the volunteers' skin using a compression bandage.

2. Supplementary Figures

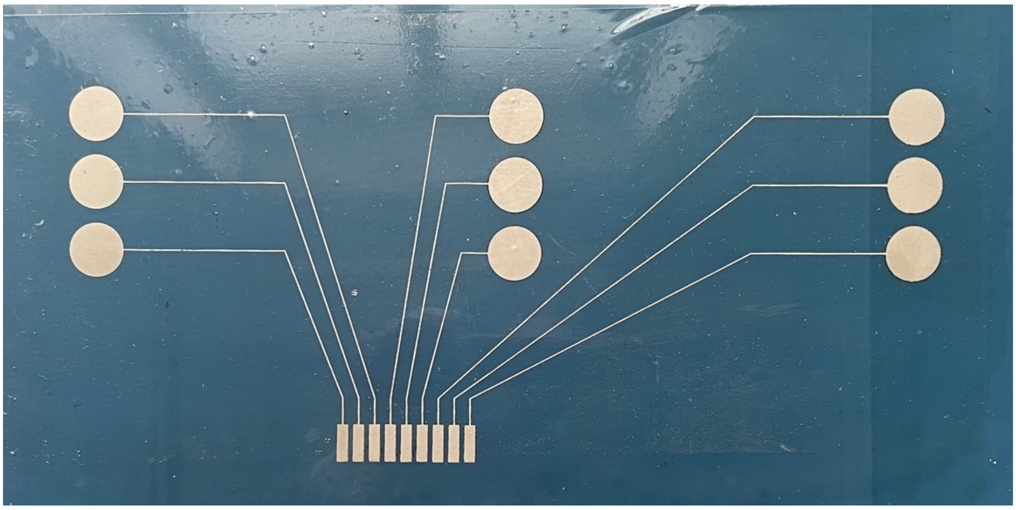

Fig. S1 3 × 3 electrode array printed on SEBS substrate by screen printing using prepared stretchable Ag ink.

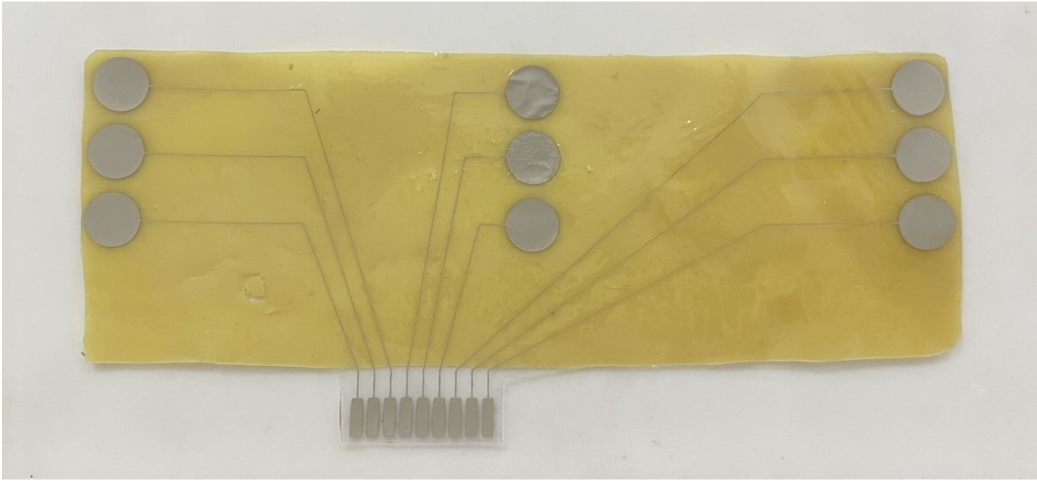

Fig. S2 Conformal on-skin electrode arrays for stable muscle–machine control.

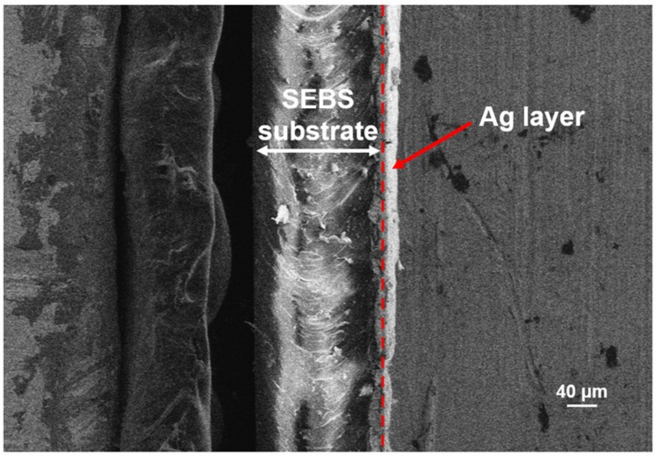

Fig. S3 The cross section of Ag/SEBS layers through screen printing.

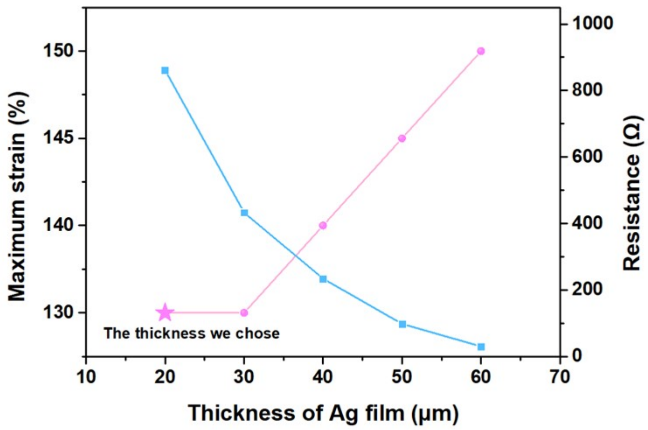

Fig. S4 The maximum strain and resistance of Ag film with different thickness.