Self-Powered Direct Muscle Stimulation Using a Triboelectric Nanogenerator (TENG) Integrated with a Flexible Multiple-Channel Intramuscular Electrode

Jiahui Wang,[1,2,3,4 ‡] Hao Wang,[1,2,3,4 ‡] Nitish V. Thakor,[1,2] Chengkuo Lee[1,2,3,4*]

[1]Department of Electrical and Computer Engineering, National University of Singapore, 4 Engineering Drive 3, Singapore 117583

[2]Singapore Institute for Neurotechnology, National University of Singapore, 28 Medical Drive, #05-COR, Singapore 117456

[3]Hybrid-Integrated Flexible (Stretchable) Electronic Systems Program, National University of Singapore, 5 Engineering Drive 1, 117608

[4]NUS Suzhou Research Institute (NUSRI), Suzhou, Industrial Park, Suzhou, P. R. China 215123

[‡]Both authors contributed equally.

Supporting Information

Contents

Section S1. Fabrication of TENG

For mechanical support during back and forth pressing operation, a PET sheet is folded in zigzag structure (Figure S1a) to store the mechanical deformation energy in the form of elastic energy so that the TENGs can automatically revert to the original position after each pressing. Then, aluminum films are attached to each surface of the folded PET sheet to serve as electrode for charge output (Figure S1b). In a pair of the aluminum films, the first aluminum film simultaneously serves dual function of both electrode and active triboelectric surface, while an additional PTFE film is assembled on top of the second aluminum film to serve as triboelectric surface (Figure S1c). To confine the structure, a PET film is applied to encompass the stacked TENG.

Section S2. Fabrication of Flexible Multiple-channel Intramuscular Electrode

The fabrication followed standard photolithography process and clean room procedures. The process started with aluminum coated silicon wafer. 10 μm bottom layer photosensitive polyimide (Durimide 7005, Fujifilm) was spin-coated on the Al wafer at a speed of 1000 rpm. After exposure under ultraviolet (UV) light, the bottom layer was post baked at 110°C and developed in HTRD2 and RER 600 (Fujifilm). Curing in N2 at 300°C for 2 h finished the process for the bottom polyimide layer with the contour shape of the electrode (Figure S2a). Next, 10 μm AZ 9260 (AZ Electronic Materials, USA) was spin-coated on the polyimide bottom layer. This AZ layer was UV exposed to define the bottom metal layer pattern. 20 nm chrome (Cr) was sputtered, followed by 200 nm gold (Au) sputtering. The lift-off process in acetone then transferred the AZ pattern to the metal layer (Figure S2b). Then, a 10 μm polyimide top layer was patterned to encapsulate the electrode, leaving only the connection pad and electrode sites exposed (Figure S2c). The fabrication was completed by releasing the electrode from the silicon wafer substrate (Figure S2d).

Section S3. Stimulation efficiency difference when flipping the electrode connection

Positive-negative and negative-positive current waveform has different stimulation efficiency. When considering the force output, stimulation waveform polarity and motoneuron distribution both matters. To simplify the discussion, we provide an example here which represents one possibility during the testing. For illustration, we assume Motoneuron1 and Motoneuron2, Electrode1 and Electrode 2 are fixed in Figure S6A and Figure S6B. In Figure S6A, both Motoneuron1 and Motoneuron2 fall in the stimulation area, and are both activated to contribute to the measured force which characterizes the summed-up effect of having both motoneurons activated. When the electrode connection is flipped in Figure S6B, Motoneuron1 still falls in the stimulation area, but Motoneuron2 is not activated. Thus, in Figure S6B, only Motoneuron1 contributes to the measured force, which will be smaller than the force measured in Figure S6A.

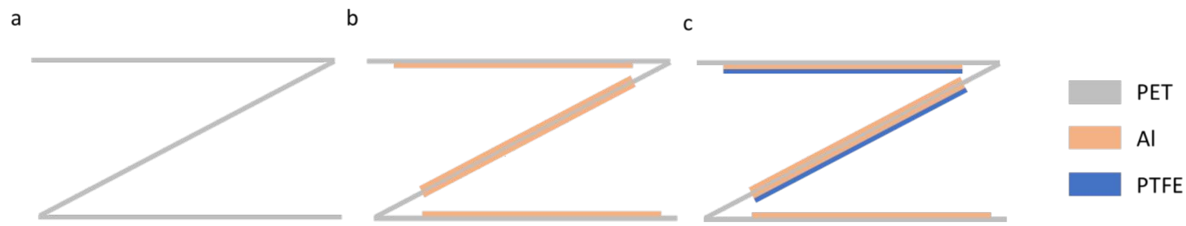

Figure S1. Fabrication process of TENGs.

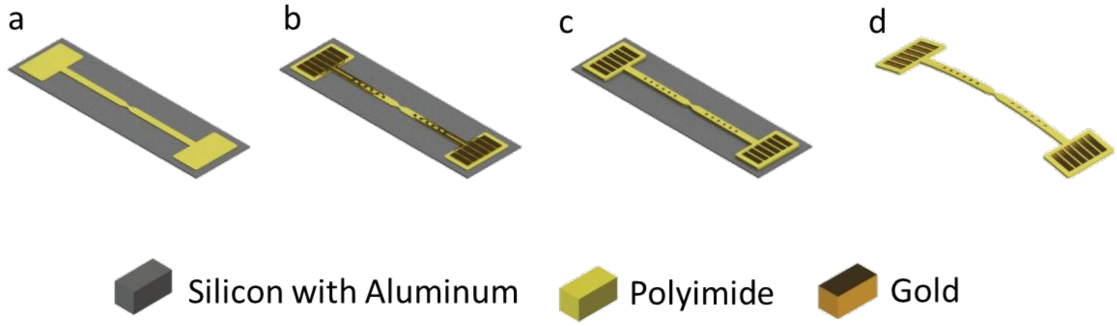

Figure S2. Fabrication process of flexible multiple-channel intramuscular electrode.

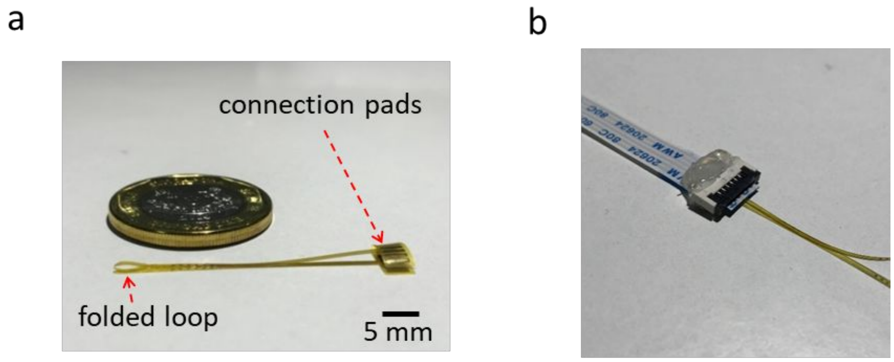

Figure S3. The flexible multiple-channel intramuscular electrode. (a) Picture of the electrode. (b) FPC is connected to the electrode.

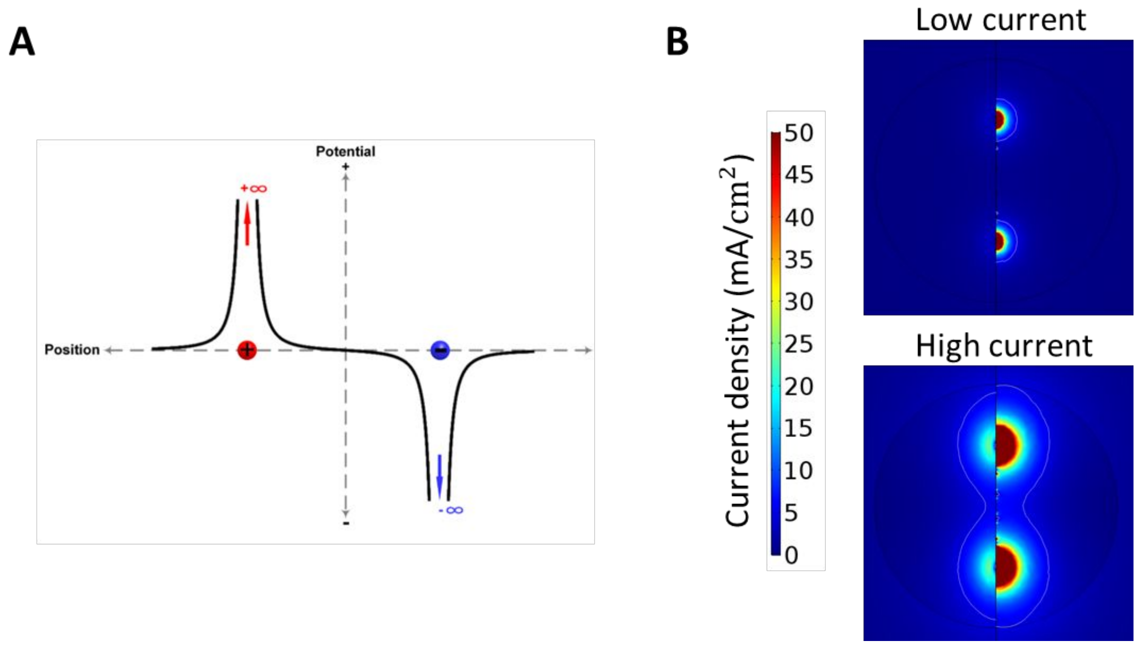

Figure S4. Simulation of electric field spatial distribution. (A) Simulation of electric field generated by static charges. (B) COMSOL simulation of current distribution generated by low-current and high-current stimulation.

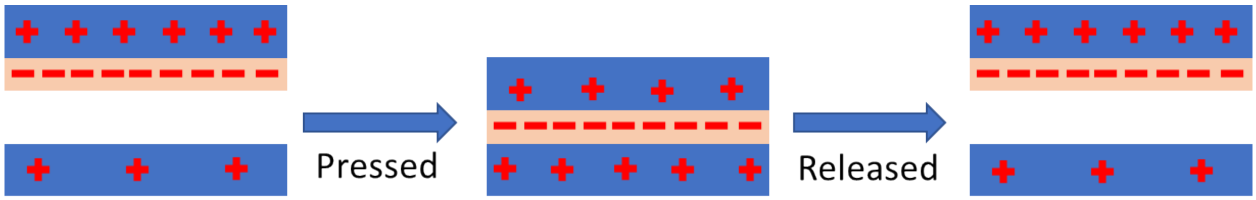

Figure S5. Working mechanism of the stacked-layer TENG.

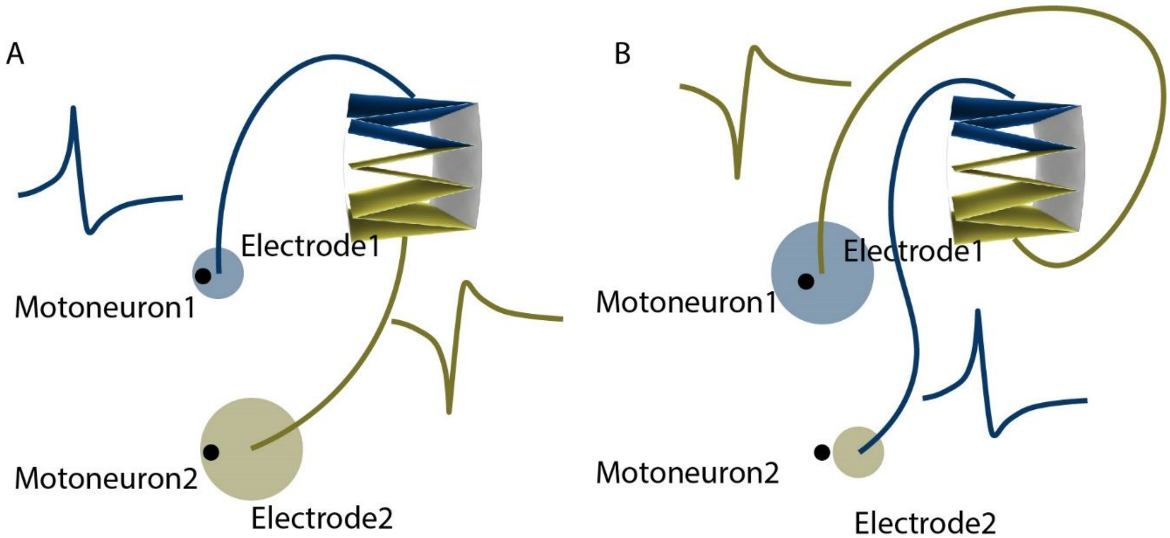

Figure S6. Flipping the electrode connection.