Batteryless neural interface using triboelectric nanogenerators (TENGs) to enable a self-sustainable platform for neuromodulation

Sanghoon Lee¹,²,³ Hao Wang¹,³, Nitish V. Thakor¹,², Shih-Cheng Yen¹,², and Chengkuo Lee¹,²,³

¹Department of Electrical and Computer Engineering, National University of Singapore, Singapore
²Singapore Institute for Neurotechnology (SINAPSE), Singapore
³NUS Suzhou Research Institute (NUSRI), China

E-mail: elec@nus.edu.sg

Abstract. The concept of converting human energy into useful power by various mechanisms has been explored as an alternative way to support the operation of implantable bioelectronics. Triboelectric nanogenerators (TENGs) have recently been proposed as a promising technology to harvest energy as an alternative power source for these implantable devices. In this paper, we investigate stacked TENGs as a potential power source for peripheral nerve stimulation. To achieve sufficient electrical energy for the stimulation, we optimize various parameters of the stacked TENGs. We combine the optimized TENGs and neural electrodes to demonstrate batteryless neural interfaces. We conduct direct and selective stimulation of sciatic nerves in rats using this batteryless neural interface to modulate different muscle activation. This prove-concept result indicates that this technology could enable a self-sustainable platform for neuromodulation in the future.

1. Introduction
The emerging field of neuromodulation using implantable bioelectronics involves modulating bodily conditions or control neuroprostheses [1][2]. One of the important challenges for long-term use of these devices is reliable power source with adequate output power. Instead of approaching wired, wireless, or implantable battery, the concept of converting human energy into useful power has been exploring as an alternative approach to support the operation of implantable devices [3]. Triboelectric nanogenerators (TENGs) have recently been proposed as a promising technology to harvest energy for these devices [3]. However, the optimization and design of TENGs for neuromodulation, which may open an attractive research direction of TENGs for direct stimulation of a peripheral nerve, has not been studied yet.

In this paper, we optimized and demonstrated stacked TENGs as a potential power source for neural stimulation of a peripheral nerve. Various parameters, such as electrical connections, the number of stacked layers, and the confinement length, were studied to generate sufficient electrical charges for the nerve stimulation. Furthermore, we demonstrated modulation of muscle functions in rats using batteryless neural interfaces combined the TENGs and neural electrodes. This result provides insight into a self-sustainable platform for neuromodulation (Figure 1). The electrical energy generated by the TENGs is delivered to a peripheral nerve via a flexible neural interface, which allows selective stimulation. Then, it activates target muscle resulting in post-biomechanical energy. This energy may finally be used for the next round of TENGs leading to a self-sustainable platform.
2. Design and Fabrication

2.1 Stacked triboelectric nanogenerators
To support folding and separating layers of the stacked TENGs repeatedly, the zigzag-shaped PET sheet was used. Figure 2 shows the working mechanism of the device. The micropyramid structure of PDMS not only improved the contact area between two layers, but also acted as the first triboelectric layer for the charge generation process. During the layers were folded, the first bottom copper film acted as the bottom electrode (Figure 2a) beneath the patterned PDMS film (Figure 2b). The second copper film served the dual purpose of being the second triboelectric layer and also the top electrode.

For the fabrication of the TENGs, a silicon substrate was etched by KOH for the inverted micropyramid patterns. These micropyramid patterns were transferred onto PDMS films using molding process. After assembling the copper films, the patterned PDMS films were attached on top of alternative facing upwards. For the confinement structure of the TENG devices, different lengths of PET films were used to encompass stacked TENG devices, where the confinement height was designed to have variations ranging from 1 to 6 cm in order to restrict the maximum separation between the top and the bottom layer.

2.2 Flexible sling electrode
The neural interfaces were fabricated using microfabrication technology. It consists of two layers of flexible polyimide with gold sandwiched in between in a sling-shape geometry. It has six active electrodes in the middle bridge and two ring electrodes in the outer two bridges, which enables tripolar or bipolar stimulation configurations [4].

3. Characterization of triboelectric nanogenerators (TENGs)
The characteristics of voltage and power were measured depending on different values of load resistances connected with parallel and series configurations, respectively. The peak power of the layers connected in the parallel was 51.8 μW at the load resistance of 15 MΩ (Figure 3a). The decrement of the maximum power in series configuration was significant when the load resistance value is reduced. It demonstrates that the parallel configuration is suitable for neural stimulation since the impedance between a neural electrode and a sciatic nerve is typically degree of kΩ.
In addition, we increased the number of stacked layers in parallel configuration to demonstrate corresponding change in the output voltage and short circuit current at a fixed frequency of 4 Hz and a fixed confinement of 4 cm. The short circuit current increases linearly from 0.3 to 1.7 μA as the number of the layers increase from 1 to 5 (Figure 3b). The output voltage and current of 5 stacked layer depending on the confinement length are shown in Figure 3c. The peak output voltage and short circuit current were saturated with the confinement lengths of 4 cm in the 5 layers. Figure 3d shows calculated charges generated depending on the number of stacked layers. For the stimulation of nerve, charge, which is the product of current amplitude and pulse width, is important. The total charge was achieved in 35 nC with the 5 layers, which is a reasonable threshold charge for stimulating a nerve based on previous study [5]. Finally, the 5 layered device with 4 cm confinement length was used for in vivo experiments.

4. In vivo test of batteryless neural interface
The direct stimulation was conducted to activate different patterns of the muscle activations using the batteryless neural interface combined this optimized TENGs and the flexible sling interface (Figure 4a). The two electrodes of the sling interface were selected for the transversal stimulation, which enables to activate a certain part of the sciatic nerve (Figure 4b). The TENG was tapped by a hand to activate the muscles and compound muscle action potentials (CMAPs) of gastrocnemius medialis (GM) and tibialis anterior (TA) muscles were recorded, respectively (Figure 4c). We observed the twitch of the muscle while the stimulation. To fully demonstrate modulation of the TA muscle, we connected the TENG to a pair of Pt/Ir wires implanted on the common peroneal (CP) nerve (Figure 4d). The TENG was tapped by a hand with different frequencies while the CMAPs of GM and TA muscles were recorded (Figure 4e-h). The increased impact force associated with higher tapping frequency leads to higher output voltage. Thereby the muscles were activated more in this case. It demonstrates that the TENG is able to generate sufficient charges to modulate TA muscle via neural interfaces.
5. Conclusion
We demonstrated batteryless neural interface by combining stacked TENGs and neural electrodes. To demonstrate this technology, we conducted direct stimulation of sciatic nerves in rats to selectively activate the TA muscle. Even though the self-sustainable platform could not be achieved yet in this stage, this result shows positive possibility of the self-sustainable technology with this batteryless neural interface in near future.

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