A Bioinspired Flexible Organic Artificial Afferent Nerve

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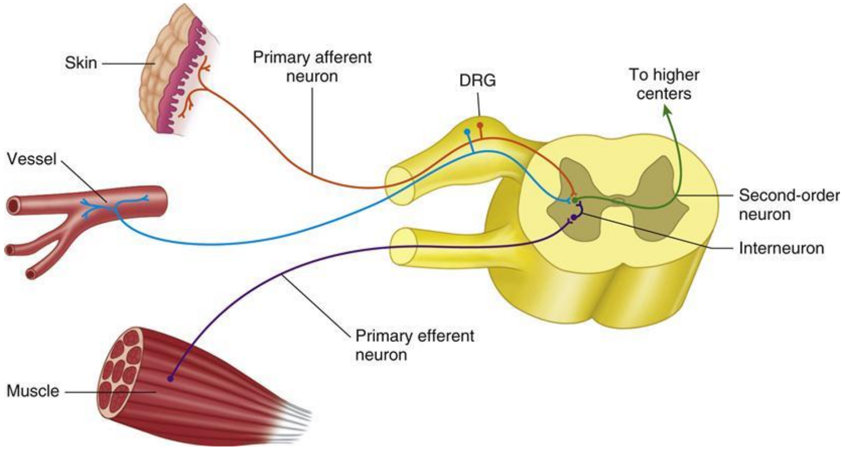
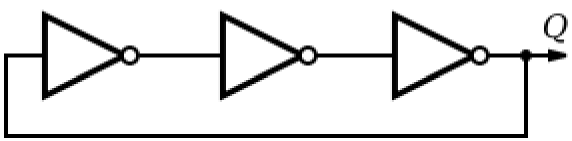
Introduction

The **somatosensory system** is the part of the sensory **system** concerned with the conscious perception of touch, pressure, pain, temperature, position, movement, and vibration, which arise from the muscles, joints, skin, and fascia.

- afferent neurons convey the sensory stimulus to the brain
- efferent neurons convey the motor stimulus to the muscles



Oscillator: An electronic oscillator is an electronic circuit that produces a periodic, oscillating electronic signal, often a sine wave or a square wave. Oscillators convert direct current from a power supply to an alternating current signal.



Ring Oscillator: It is a device composed of an odd number of NOT gates in a ring, whose output oscillates between two voltage levels, representing *true* and *false*. The NOT gates, or inverters, are attached in a chain and the output of the last inverter is fed back into the first.

https://pocketdentistry.com/wp-content/uploads/285/F00002Xf02-01-9780323082204.jpg

Introduction to the paper

- Device structures that emulate the functionality and signal processing of biological components may potentially simplify complex circuits by mimicking multiple synapses with a single device.

- Organic devices are attractive because their characteristics can be tuned through chemical design, they are compatible with printing methods that enable large-area coverage at a lowcost, and they have relatively low elastic moduli, similar to those of soft biological systems.

- In this paper, an artificial afferent nerve based on flexible organic electronics was described.

- The bioinspired artificial afferent nerve here emulates the functions of biological SA-I afferent nerves by collecting data from multiple tactile receptors and conveying this information to biological efferent (motor) nerves, completing a hybrid bioelectronic reflex arc.

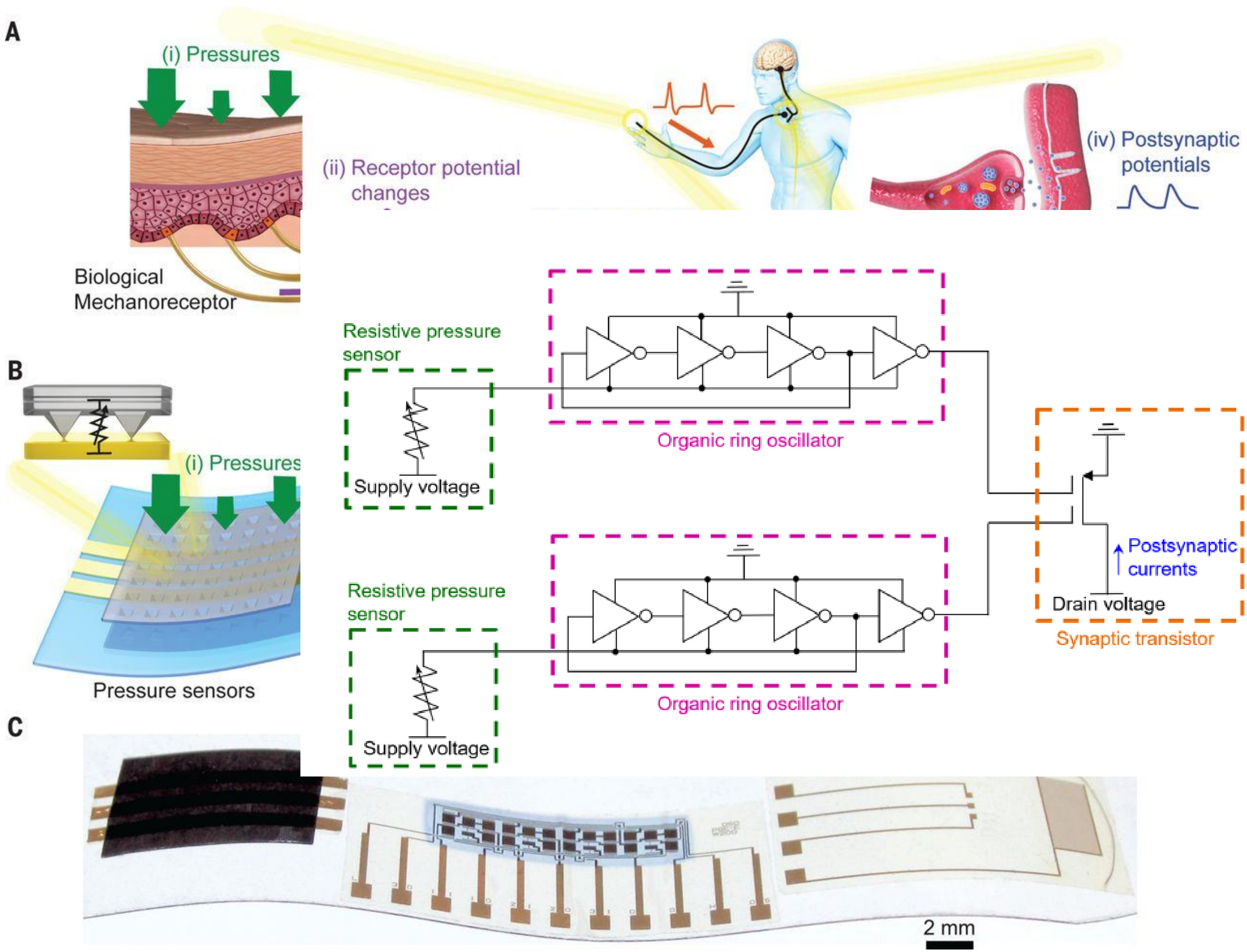
- These artificial afferent nerve collects pressure information (1 to 80 kilopascals) from clusters of pressure sensors, converts the pressure information into action potentials (0 to 100 hertz) by using ring oscillators, and integrates the action potentials from multiple ring oscillators with a synaptic transistor.

- Biomimetic hierarchical structures can detect movement of an object, combine simultaneous pressure inputs, and distinguish braille characters.

- These artificial afferent nerve were connected to motor nerves to construct a hybrid bioelectronics reflex arc to actuate muscles.

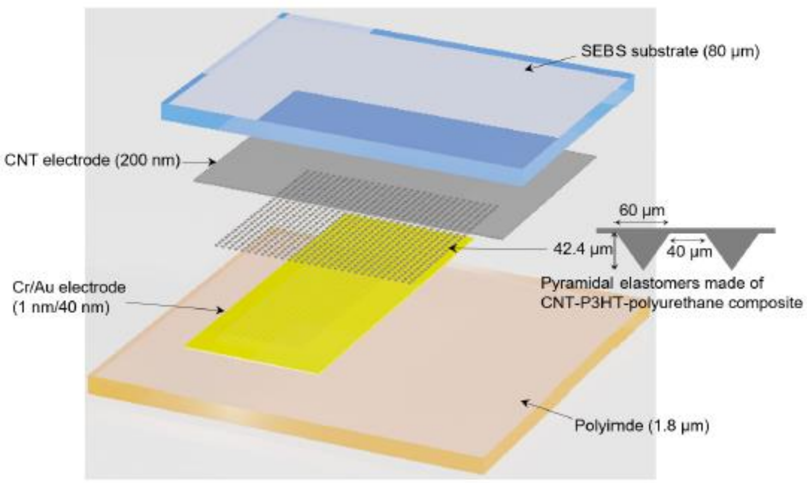
- This system has potential applications in neurorobotics and neuroprosthetics.

An artificial afferent nerve system in comparison with a biological one.

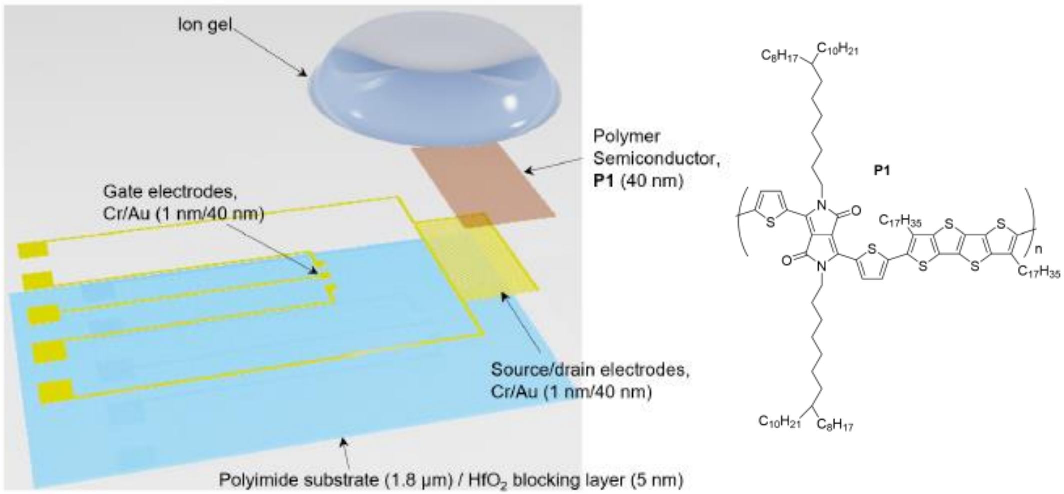


An artificial afferent nerve system in comparison with a biological one.
(A) A biological afferent nerve that is timulated by pressure. Pressures applied nto mechanoreceptors change the eceptor potential of each nechanoreceptor. The receptor potentials ombine and initiate action potentials at he heminode. The nerve fiber forms ynapses with interneurons in the spinal ord. Action potentials from multiple nerve bers combine through synapses and ontribute to information processing.
B) An artificial afferent nerve made of ressure sensors, an organic ring oscillator, nd a synaptic transistor. Only one ring scillator connected to a synaptic ransistor is shown here for simplicity. Iowever, multiple ring oscillators with lusters of pressure sensors can be onnected to one synaptic transistor. The arts with the same colors in (A) and (B) correspond to each other.
(C) A photograph of an artificial afferent nerve system.

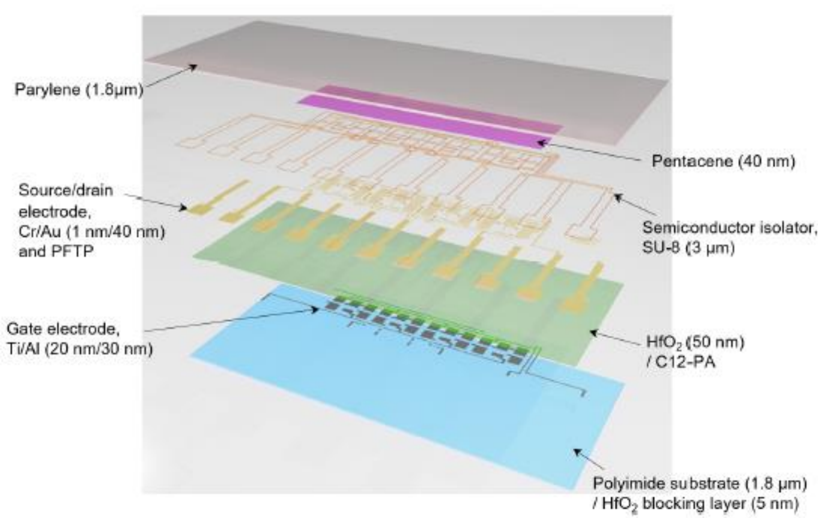
Device Fabrication



Structures of resistive pressure sensor. Contact resistance between pyramids made of CNT-P3HT-polyurethane composite and an Au electrode determined the resistance between CNT and Au electrodes. The composite ratio was determined to get optimal sensing characteristics.

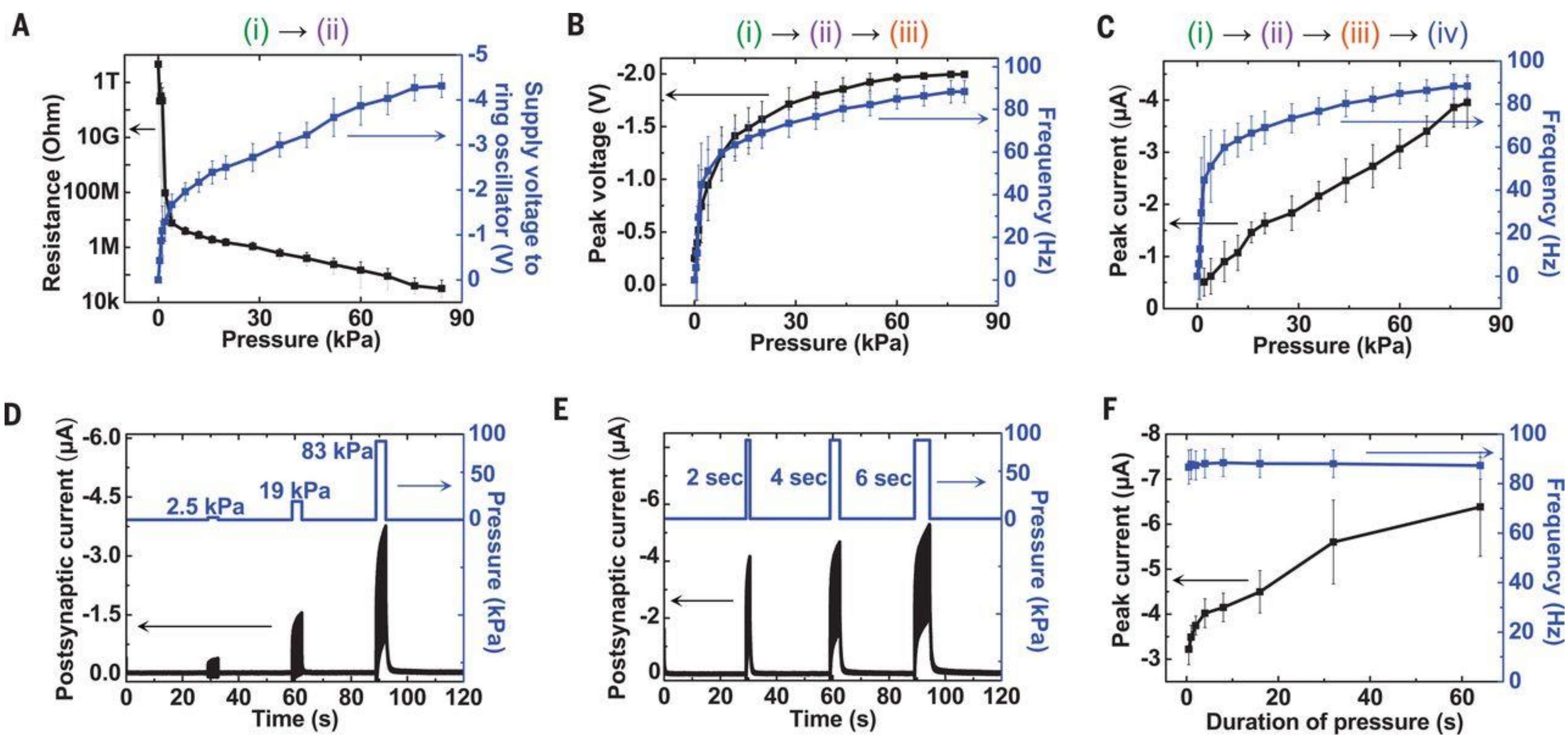


Structure of synaptic transistors and a polymer semiconductor.
(A)Gate electrodes and source/drain electrodes were on the same plane. Polymer semiconductor covered channel area between source/drain electrodes. Ion gel covered both channel area and gate electrodes. Multiple gate electrodes can be used for one channel, which enables multiple inputs to the synaptic transistor. The width and length of the transistor channel were 202.000 mm and 20 μm, respectively.
(**B**) Structure of the polymer semiconductor used in synaptic transistors



Device structure of organic ring oscillators.
Organic flexible transistors with bottom gate and bottom contact structures were used to make the ring oscillators. We utilized photolithography and shadow masks to pattern different layers. HfO2/C12-phosphonic acid gate dielectric enabled low voltage operation. Pentacene semiconductor was thermally evaporated under vacuum. SU-8 structures were used to separate pentacene films between transistors because pentacene is disconnected due to the 90° steep sidewall of SU-8.

Characteristics of an artificial afferent nerve system with one branch.



Characteristics of an artificial afferent nerve system with one branch.

(**A**) Resistance of a resistive pressure sensor and the corresponding change in the supply voltage of an organic ring oscillator in response to the change of pressure.

(**B**) Peaks and oscillating frequencies of output voltages of ring oscillators as a function of pressures applied to pressure sensors.

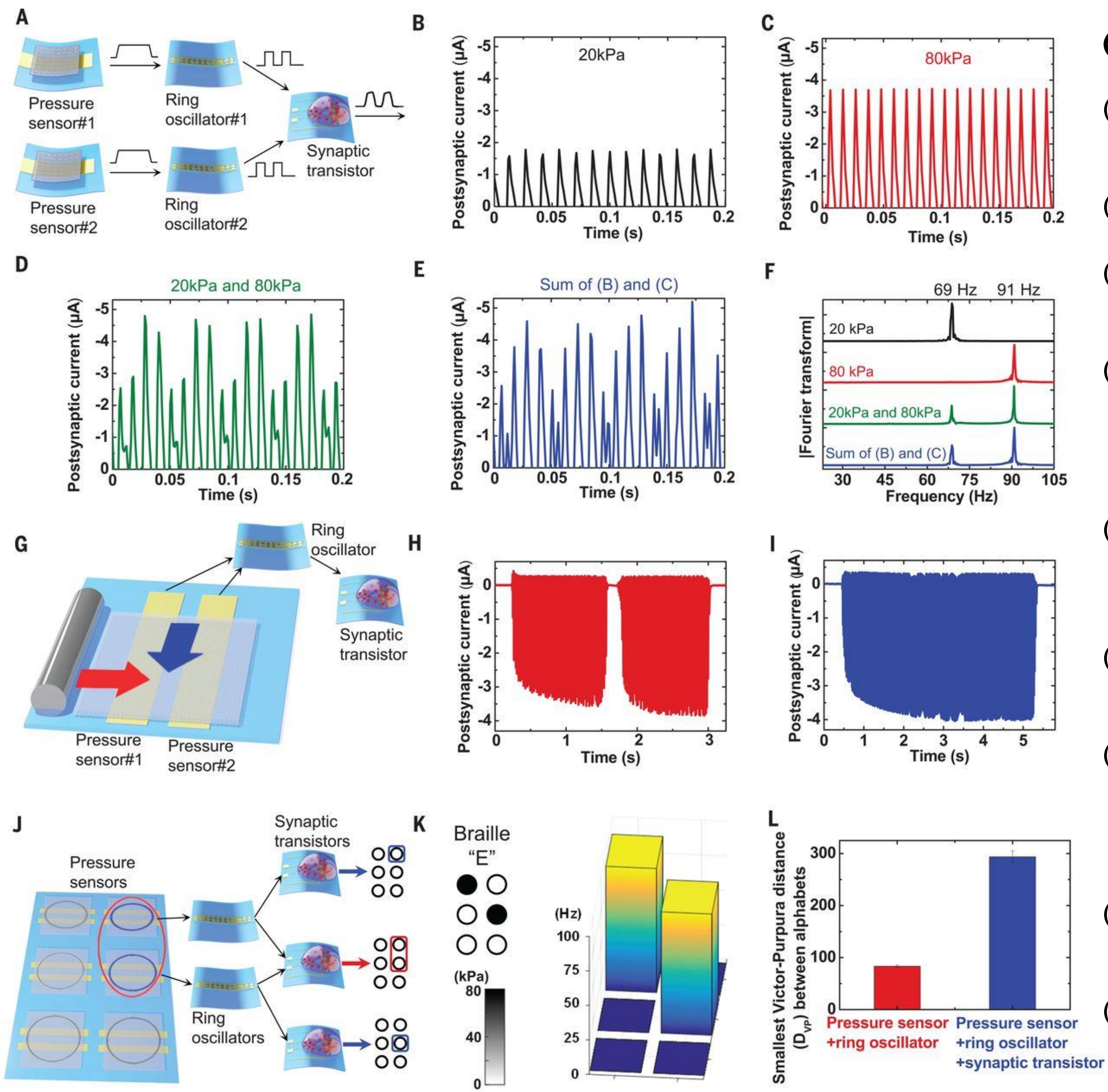
(**C**) Peak values and oscillating frequencies of postsynaptic currents of synaptic transistors depending on pressures. The gate voltage of the synaptic transistor was supplied from the ring oscillator output.

(**D**) Postsynaptic current output of an artificial afferent nerve for three different pressure intensities. The duration of the stimulus application was 4 s for all three cases.

(**E**) Response to three different durations of the pressure stimulus with a constant pressure intensity of 80 kPa.

(**F**) The peak amplitude and frequency of the postsynaptic current depending on the duration of the stimulus application for the fixed amplitude of pressure (80 kPa). All error bars in (A) to (F) show 1 SD. (i) to (iv) correspond to the signals in Fig. 1. Arrows indicate the conversion of the signals by pressure sensors, organic ring oscillators, and synaptic transistors.

Characterization of an artificial afferent nerve system with multiple branches.



Characterization of an artificial afferent nerve system with multiple branches.

(A) Artificial afferent nerve with two branches of ring oscillators and pressure sensors measured in (B) to (F).

(**B** and **C**) Postsynaptic currents when only one pressure sensor was pressed with 20 kPa (B) and 80 kPa (C), respectively.

(**D**) Postsynaptic current when pressures of 20 and 80 kPa were simultaneously applied to two pressure sensors.

(**E**) Plot of the sum of currents from (B) and (C). The synaptic transistor functions as an adder so that (D) and (E) are almost the same.

(**F**) The amplitude of Fourier transform of the cases in (B) to (E). Frequency components corresponding to pressures are maintained after the pressure information is combined by a synaptic transistor. Each transform was done for 4 s of data and normalized to its maximum peak.

(**G**) Artificial afferent nerve with a cluster of two pressure sensors used for movement recognition in (H) and (I). The width of electrodes was 800 μm, and the distance between the two electrodes was 400 μm.

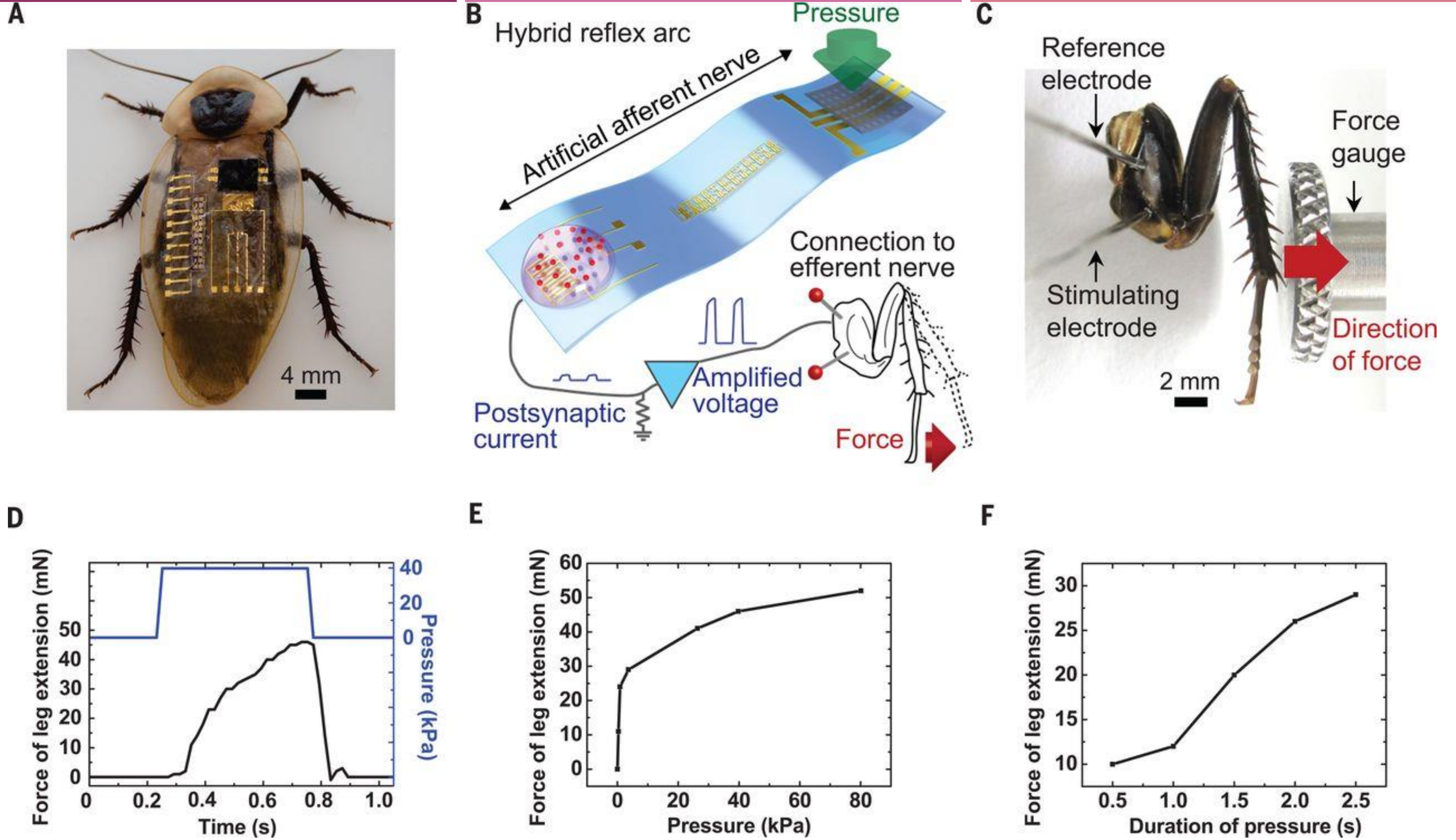
(**H** and **I**) Postsynaptic currents when an object is moved in the direction of the red arrow (H) and the direction of the blue arrow (I) in (G).

(**J**) Portion of the connections used for braille reading in (K) and (L). Ring oscillators and synaptic transistors were connected to an array of three pixels by two pixels of pressure sensors. A synaptic transistor was connected to either one or two ring oscillators.

(**K**) (Left) Applied pressures on the pressure sensor array. (Right) Peak frequencies of postsynaptic currents from synaptic transistors connected to only one pixel

(**L**) The smallest Victor-Purpura distance (the metric used to quantify the difference between postsynaptic currents) between the postsynaptic currents of different alphabets. The integration of signals from two pixels by synaptic transistors improves the discrimination among the braille characters.

Hybrid reflex arc.



Hybrid reflex arc.

(**A**) Discoid cockroach with an artificial afferent nerve on its back.

(**B**) Hybrid reflex arc made of an artificial afferent nerve and a biological efferent nerve. This experimental setup was used for measurements in (D) to (F). Pressure stimuli from multiple spots can be combined by an artificial afferent nerve and can be converted into postsynaptic currents. Postsynaptic currents are amplified to stimulate biological efferent nerves and muscles to initiate movement.

(**C**) Photograph of reference and stimulating electrodes, a detached cockroach leg, and a force gauge used for (D) to (F). The tibial flexor muscle was dissected to remove its disturbance.

(**D**) Isometric contraction force of the tibial extensor muscle in response to pressure on the artificial afferent nerve in (B). The pressure intensity and duration were 39.8 kPa and 0.5 s, respectively.

(**E**) Summary of the maximum isometric contraction force of the tibial extensor muscle depending on the intensities of pressures. The duration of the stimulus application was 0.5 s for all measurements.

(**F**) Effects of the duration of the pressure stimulus on the maximum isometric contraction force of the tibial extensor muscle. The amplitude of pressure was fixed at 360 Pa.

Conclusion

- On the understanding of biological afferent nerves, an artificial afferent nerve based on organic devices that have multiple hotspots in the receptive field, generate action potentials depending on the combined pressure inputs, and integrate action potentials at a synaptic transistor was fabricated.

- The biomimetic hierarchical structures were used to detect the shape and movement of an object in simple cases and to distinguish braille characters.

- Finally, artificial afferent nerve was connected to biological efferent nerves to demonstrate a hybrid bioelectronic reflex arc and control biological muscles.


Don't watch the clock; do what it does.
Keep Going.
QUARTZ
Thank you…